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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARDograph 332

Stick and Feel System Design

(Systèmes de restitution des efforts au manche)

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(Systèmes de restitution des efforts au manche)

by

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Stick and Feel Systems

(AGARDograph 332)

Executive Summary

Modern aircraft/rotorcraft are heavily reliant on systems to assist the pilots in controlling the aircraft. This volume provides a compendium of lessons learned, as well as a state-of-the-art review of stick and feel flight control systems. It considers aerodynamic feel devices, powered control systems, and artificial feel devices. Particular effort is made to discuss the "whys" of design, emphasizing modern irreversible flight control systems. The volume also proposes a path forward for future flight control research efforts.

This AGARDograph should be valuable to anyone currently:

— involved in designing or developing flight control systems;

— concerned with integrating flight control systems into air vehicles;

— doing basic research in flight control systems.

Studying the lessons learned and the approaches discussed in this volume will facilitate research and development of flight control systems that can maximize the ever increasing performance potential of modern aircraft, without physically or mentally overloading the pilot. This should result in enhanced combat effectiveness and aviation safety for NATO's aviation assets.

Systèmes de restitution des efforts au manche
(AGARD AG-332)

Synthèse

Les aéronefs à voilure fixe et à voilure tournante modernes font un large appel à différents systèmes d'aide au pilote pour assurer le contrôle de l'aéronef. Ce volume représente un condensé des enseignements tirés dans ce domaine au cours des dernières années, ainsi qu'un résumé de l'état actuel des connaissances des systèmes de restitution des efforts au manche. Il examine les dispositifs de sensation artificielle aérodynamique, les servocommandes et les circuits de sensation musculaire. Un effort particulier est fait en ce qui concerne l'examen de la philosophie de conception, en mettant l'accent sur les systèmes de commandes de vol modernes irréversibles. L'ouvrage propose aussi un axe de développement pour les travaux de recherche futurs.

Cette AGARDographie intéressera toute personne actuellement impliquée dans :

— la conception et le développement des systèmes de commandes de vol;

— l'intégration des systèmes de commandes de vol dans les véhicules aériens;

— la recherche fondamentale en systèmes de commandes de vol.

L'étude des enseignements tirés et des approches examinées dans ce volume doit faciliter la recherche et le développement de systèmes de commandes de vol capables de porter au maximum les performances toujours croissantes des aéronefs modernes, sans imposer une quelconque surcharge de travail physique ou intellectuel au pilote. Il doit en résulter une meilleure efficacité au combat et une meilleure sécurité de vol pour les avions de l'OTAN.

Contents

Preface

Since the earliest days of manned flight, designers have to sought to assist the pilot in the performance of tasks by using stick and feel systems to bring these tasks within the bounds of human physical capabilities. This volume describes stick and feel systems in two parts. Part one describes the technologies which have been developed throughout the history of 20th Century aviation. Part two describes how modern systems dynamics interact with the human pilot.

Part one begins with an historical overview and goes on to describe aerodynamic feel devices, powered control systems, and artificial feel devices, providing a review of the state-of-the-art, capabilities and limitations of each and providing a history of lessons learned from past applications. Part one then goes on to discuss the critical area of control harmony, and concludes with a summary of the future of stick and feel.

Part two discusses the "whys" of design, with a particular emphasis upon the modern irreversible flight control system. It recommends that a closed loop perspective be used for all future research efforts. With the increasing performance and capabilities of modern aircraft/rotorcraft, the information processing and actuation limitations of the human pilot play an even more critical role in the overall success and safety of these vehicles than in the past. We can no longer expect pilots to compensate for design shortcomings in an environment characterized by a tendency to overload the pilot with sensory data.

It is hoped that the design lessons and approaches outlined in this volume will contribute to a better understanding and appreciation of the importance of force-feel system design in aircraft/rotorcraft flight control.

AGARDograph 332
STICK AND FEEL SYSTEM DESIGN

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INTRODUCTION

Part 1 of this report describes the development of stick and feel systems from the first experiments of the Wright Brothers in 1900 up to the present date. From the chaotic and uncertain beginnings of an understanding of aircraft control, there emerged a consistent agreement on the basic cockpit control layout that remained almost unchanged for many decades. To assist the pilot in performance of tasks within the bounds of human physical capabilities, attention turned to the tuning of control forces through a wide variety of control surface aerodynamic balancing methods, augmented eventually by mechanical devices such as springs and bobweights. These developments essentially covered the period to the 1940's though the results are equally applicable today for appropriate aircraft types.

Already by the 1940's, however, the need for new methods to assist the plot was becoming obvious, firstly due to increasing size and airspeeds, and then to entry into previously inaccessible aerodynamic regimes near and then above Mach 1. This led to the introduction of powered control actuation and a range of new mechanical influences on control qualities. A new science of artificial feel evolved, ranging from little more that simple springs to highly developed variable feel and gearing systems. With the parallel development of stability augmentation, these mechanical methods enabled satisfactory flight control to be accomplished over the complete range of flight conditions from zero airspeed up to Mach 3 and beyond to the borders of space flight. These methods will continue to be applicable for many years to come in the future.

However, the newest technology of fly by wire is spreading from the early research aircraft, firstly to the fields of highest performance combat aircraft - and one airliner, the Concord - to a more general acceptance that this is likely to be the way of the future for an increasing variety of types. Its now universal use in the larger airliners is certain to be repeated in smaller types as the economic and technical benefits become more apparent. Generally, this era has led to a considerable simplification in the design of stick and feel systems, the complexity once residing in them being taken up by the flight control system computers. This simplicity is not entirely desirable in all cases, and it is certain that further developments in feel are yet to come.

These several phases in the developments of stick and feel are reviewed in some detail, with many examples of mechanisms and examples of success and failure.

Part 2 of this report describes the manner in which the control stick and force-feel system dynamics interact with the human pilot. The discussion begins with an overview of the problems and promises of the modern, irreversible fly-by-wire flight control system. It is asserted that a closed-loop perspective is essential to a unified treatment of force-feel system analysis and design. Given this analytical philosophy, attention is focused upon pilot/vehicle system representation, one of the most important being modeling the pilot's neuromuscular system. Since the force-feel system is the primary interface between the pilot and aircraft, the influence of force-feel system characteristics upon vehicle handling qualities is discussed next. The somewhat ambiguous way in which various military handling qualities specifications have treated the force-feel system are presented. The manner in which vibrating and accelerating environments interact with force-feel systems is next discussed including the effect of vehicle elastic degrees of freedom. Finally, a brief discussion of the effect of force-feel system nonlinearities concludes the report.

PART 1: THE DEVELOPMENT OF STICK AND FEEL SYSTEM DESIGN

1.0 HISTORICAL OVERVIEW

Before examining the detailed system features that have determined the characteristic qualities of "stick and feel", it is worth while to take an overview of their historical development from the beginning to the present day.

1.1 Controller layout

From a little after the beginning of manned powered flight nine decades ago, there has been remarkably little change in the fundamental layout of the pilot's stick and pedals. Pilots seem to have adapted fairly easily to wide ranges of forces, displacements and force/displacement gradients, however. Perhaps because of this adaptability, no standard design specifications applicable to all or many aircraft exist. The apparently desirable goal of common designs available "off the shelf" to different aircraft manufacturers was seldom seriously considered, except for example the standard Fairey rudder pedals used on many British aircraft of the 1940's and 1950's and a recently developed family of fly by wire sticks for some current combat types. The quite recent advent of wrist-actuated controllers has followed on from the new environment and technology of fly by wire aircraft and space vehicles rather than from inherent needs of control.

Although the Wright Brothers evolved their ultimately successful control techniques between 1900 and 1905, their controllers were of a wide and often very unsatisfactory variety up to 1911 (Walsh, Oppel, Coombs 1974). In the gliders of 1900 and 1901, the wing warping was effected by a foot controller, while the foreplane angle was more or less directly operated by holding extensions to its trailing edge. The pilot pushed down to pitch up, therefore, and *vice versa*. In the radically improved 1902 glider, wing warping was effected by lateral movement of the hip cradle, taking advantage of the instinctive corrective reaction to move it away from a lowered wing. The foreplane, now well out of reach, was operated by a stick moved forward to pitch down, and Wilbur Wright was once confused by the reversed effect. After adding a fixed fin, and then realising the necessity for turning it into a movable rudder, they connected it to the warping wires, the first-ever aileron-rudder interconnect, avoiding the complexity of using a third pilot controller. This was the configuration for the first successful powered manned aircraft, the 1903 Flyer.

When they realised in 1905 that the rudder would have to be controlled separately, they connected it to a right hand controller. With the upright dual seats installed in 1908 for the Army trials and the French tour, the lateral controllers were modified drastically. The left seat retained the left hand pitch lever, but the right hand lever was now used for wing warping, moved aft for left roll and forwards for right roll. The rudder was controlled by lateral deflection of the top part of the right stick. This arrangement caused them some confusion. When they renewed practice flying at Kitty Hawk early in 1908 after more than two years without flying, it led to a serious accident. In his apparently flawless demonstrations at Le Mans later in 1908, Wilbur afterwards confessed to making many though instantly corrected mistakes. In fact, after only five days there, he crashed when attempting to pitch up and raise the left wing while too low in a left turn, inadvertently pushing both sticks forward instead of pulling the left one back.

The only addition for dual control was a second pitch stick to the right of the instructor's seat. The pupil in the left seat used the right hand for the difficult roll-yaw control task, but the instructor had to learn to use the left hand for this. Afterwards, some instructors could not fly from the left seat. On the basis that the roll-yaw task was the most difficult, the Flyer could be supplied with sticks exchanged for left handed pilots. One pupil, unable to grasp the principles, was killed when trying to fly on his own without permission.

Almost without exception, the early European aircraft used controller principles that would be familiar today. Esnault-Pelterie, who had invented the first crude ailerons for his unsuccessful 1904 glider, also invented the control stick in 1907 for his REP aircraft. There was no rudder bar, however, since it had no rudder. Bleriot patented a dual pitch-roll control stick in 1908 with a small horizontal wheel on its top. This did not rotate and was merely a handhold, the forerunner of the vertical twin bars or circular two-handed grip seen on many fighter aircraft up to the 1940's. Bleriot aircraft were also fitted with a rudder bar, and the engine controls were mounted on the stick. This type, widely used in flying schools before 1914, was influential in setting a standard layout for the aircraft of the First World War. The Antoinette had two control wheels in the fore-and-aft plane, the right one controlling pitch and the left one controlling wing warp, with a rudder bar. Breguet finally set the standard for wheel controllers in 1911 (Coombs 1990) with a rudder bar, a wheel for roll control and fore and aft motion for pitch control. This evolved from a version without a rudder bar, the ailerons or wing warping being operated by lateral stick motion while the rudder was operated by the wheel, permitting a degree of aileron-rudder co-ordination using only the stick.

Most variations were of little significance, e.g. the stick might be central to the pilot, or on the right as in the Howard Wright Biplane (no connection with the brothers) and the Bristol Boxkite, with the throttle hand control typically on the left. The Farman Longhorn trainer used a pivoted "handlebar" at the top of the stick, a truncated form of wheel. Fighter types generally used the stick, invariably in the centre. Though the wheel sometimes appeared on smaller types such as the Albatros C.III two seater in production from 1915 to 1918, it was mainly used in particular for the larger types. This was practically essential for aircraft with high aileron hinge moments because two hands could be applied through a much larger travel than with a stick. On the extremely large Handley Page V/1500 bomber of late 1918, the control wheel was almost 600 mm in diameter, a practice continued to the 1930's in the H.P. 42 biplane airliner.

According to Post, whereas French types were "steered by the feet and balanced by the hands", American machines differed radically in that usually they were "steered by hand and balanced by shoulder or body movements". Post categorizes the latter as typified by the Curtiss, "copied more than any other by other builders", and considered it "perhaps the most natural to operate". It had a wheel, pushed fore and aft for pitch control, and connected to the rudder for steering. The ailerons (individual "little wings" mounted half way between the upper and lower wings) were operated by rocking the pivoted seat-back from side to side by body movements. The pilot's left foot operated the throttle and the right the engine cut-off. The survey by Loening (1911) of existing controllers was uncertain about the correct arrangements, as "what appears instinctive to one man might appear very difficult to another". However, nobody would have disagreed with his statement (1916) that "The usual pitching control of pushing forward on a post to go down and pulling back to increase the angle, is very instinctive".

It is worth briefly considering how the early perception and practice of lateral-directional control might have influenced early controller design. The Wrights always knew that turning required the aircraft to be banked, later adding the rudder only to control sideslip. It had been universally believed elsewhere that turning should be a yawing manoeuvre effected by the rudder,

as in a boat, with the wings preferably level. As late as 1908, Farman won a prize for the first Frenchman to complete a full circle, his aircraft skidding and jumping flatly in a nervous series of quarter-turns (Walsh). Astonishingly, this belief continued to dominate the practice of steering for many years, even after the 1908 Flyer clearly demonstrated to all eyes the advantage of banking to produce a turn.

It seems that, though the Wrights taught many pilots and were perfectly open about their control technique, other fliers simply refined the skidding turns by adding some bank angle (respectively the steering and balance actions noted by Post). It was widely stated, and was taught officially to Royal Flying Corps pupils during the 1914-18 war, that an aircraft would take up the required bank angle by itself due to the higher airspeed of the outer wing tip. Lewis was told, however, "Don't you believe it. Get her banked correctly on your bubble, otherwise you'll turn flat and chase your tail - spin, I mean," despite which nobody doubted the necessity for using the rudder as the primary turning control. Indeed, there were many accidents due to "tail chasing". Post comments on the need to pitch down when turning a low powered aircraft due to the loss in speed because of the drag caused by the machine slewing sideways. Lewis also describes struggling to clear the airfield buildings in the two seater Morane Parasol observation aircraft, sideslipping with full aileron applied to pick up a wing dropped in turbulence but to little effect, and apparently unaware that the rudder could have been used to prevent the slip.

Initially the effectiveness of banking was attributed (e.g. Kaempffert) to gravity acting on the weight to counter the centrifugal force applied to the airframe by the turn, though he states that control by ailerons or wing-warping is necessary to counter any excessive self-banking tendency due to the skidding turn. This fallacy was eventually superseded by one somewhat nearer the truth, Loening (1916) stating the need to generate a centripetal force, with vertical component equal to the weight, by adjusting the bank so as to obtain this force "sufficient to hold the aeroplane to the degree of turn dictated by the amount of rudder movement given". Despite this insight, he still refers to the fictitious centrifugal force that would slide the aircraft outwards and uphill - "the path of least resistance" - if a stall was caused by trying to turn too tightly. Although he cautions against the use of excessive rudder which had caused many skidded stall accidents, the connection between the turn and the lift vector was only indirectly made through the "inversion of rudder and elevator ... on a steep bank the elevator becomes the rudder, and to keep the degree of turn the elevator must be pulled in". This famous fallacy thus owes its origin to the perception of turning as a manoeuvre controlled in earth axes rather than in aircraft axes.

It must be acknowledged that the poor ailerons of the time with large adverse yaw would not have made the truth easy to discern. Nevertheless it remains an oddity that the Wrights got the turning control technique right with the wrong controllers, while most others managed the opposite. The Wrights did not adopt conventional controls until 1911, though photographs of the period show that they then tried a variety of types. These were the pitch-roll stick and rudder bar; their old controllers for the left seat and the Breguet wheel for the right, oddly with rudder bars for both seats; and the standard Breguet wheels with rudder bars for both seats. Probably by about 1914, the controller format was more universally settled in the arrangements used to this day. Pilots could transfer from one type to another and expect the "natural" control relationship.

The reasons for choice of a wheel at the time must have been associated with the common turning control on an automobile, quite obviously so in the case of the Curtiss in which the controls could hardly have resembled those of a car more closely. This was even more direct on the Aerial Experiment Association's 1908 June Bug, where the wheel also steered the nose wheel of the tricycle undercarriage. On the other hand, adjusting the bank angle to move the bubble to the centre (the turn and slip instrument is still sometimes referred to incorrectly as the turn and bank) or to maintain the wings level would seem at least as naturally associated with the lateral movement of a stick as with rotation of a wheel. A wheel was used on small as well as large aircraft, and so could not always have been necessitated by two-handed forces. Military combat and trainer aircraft almost invariably continued to use a stick. The occasional exception, such as the wheel in the 1940's Lockheed P-38 Lightning and Bristol Beaufighter and the control column in the 1960's Avro Vulcan bomber, proved the rule. The De Havilland Mosquito used either a stick or a wheel depending on the role of its many versions.

Nevertheless, the wheel was always a common device where substantial manoeuvring was not required. It is more readily adapted to than a stick by both left and right handed pilots whether the throttle is on the left in a tandem seating arrangement or in the centre of a side by side cockpit. For tens of thousands of light and general aviation aircraft pilots, a wheel was a familiar object to ease their transition from the world of the automobile. This factor was of course far more significant in the car-dependent society of the USA than in Europe, where the stick remains more common to this day.

The undoubted confusion caused to many student pilots by the simple rudder bar arises from its early faulty association with steering and the fact that it it appears to work in the opposite sense to bicycle handlebars. Ironically, any cyclist riding at significant speed finds that pushing the left bar forward causes the machine to lean over and turn to the left. Given the earliest notion of steering an aircraft like a boat, the standard rudder bar was a natural choice which works in the same manner as the rudder ropes of a boat. It is certainly properly arranged for its true fundamental basis as a device to prevent sideslip, because the hand and foot motions to initiate or end a co-ordinated turn are almost always to the same sides in most aircraft. The reverse rudder bar arrangement used in a few exceptions did not survive beyond 1910 (Coombs 1990).

1.2 Control feel developments

The concept of "feel" by adjustment of control surface aerodynamic balance was initially unknown. Lewis, posted to fly the Morane Parasol in 1916 with only 19 solo hours, described it as "a death trap, thoroughly dangerous to fly, needing the greatest care and skill". While this was in part due to a rudder "too small to get you round quickly" (!) and poor yaw-provoking ailerons, it had a balanced all-moving tail with no feel at all. The stick, "which in any respectable aeroplane stands up straight and at a comfortable height to get hold of", did not extend above the knees and was excessively short. "The least movement stood you on your head or on your tail", and if the stick was released it fell forward and the aircraft went straight into a nose dive. Nevertheless, control balance was not absolutely essential for good handling if (by good luck, it sometimes seems) there was positive stick free stability, as in the delightful Sopwith Pup, and in 1917 Lewis recorded the Sopwith Triplane as the best for actual pleasure of flying that he ever took up.

The first examples of balance appeared on rudders, especially where there was no fixed fin or only a very small one. The balance here was not to reduce the control effort but to assist the rudder in its function as a stabilising fin, the arrangement resulting from the attempt to achieve inherent spiral stability by low directional stability and large dihedral effect. (The principal result of this theoretical misconception (that spiral stability was of overwhelming importance to pilots) was poor lateral and directional control contributing to many of the "tail-chasing" accidents noted above.) The original linkage to boats was still evident in Diehl (1936), with simple rules for balance based on naval architects' rudder design practice. The horn balance was extended to ailerons and elevators on some Fokker designs of the 1914-1918 war, the aerodynamically advanced D-VII setting excellent standards of handling qualities for all pilots from

novice to expert. Few other designers adopted them at the time, however.

At that period, too, the ability to trim for hands-off flight was seldom provided. The variable incidence tail, a Sopwith patent, appeared on his Triplane (which Lewis says could be set to perform hands-off loops indefinitely), and on the De Havilland DH.4, for example. The use of trim tabs appears to have been developed during the 1920's. The tab was soon adapted as a balance device to provide hinge moment reduction, either alone or with trimming adjustment, by linking it directly to the tail, or as a servo-control tab by operating it directly from the stick. Mechanical trimming in the form of an adjustable-datum spring attached to the pitch control cables was occasionally used, e.g. the De Havilland Cirrus, Gipsy and Tiger Moth series from 1925 onwards. New forms of control balance were developed in the 1920's, especially for ailerons where the horn type tends to degrade the tip aerodynamic design and is also liable to flutter. Diehl illustrates the Handley Page set-back hinge, the Frise balance, and the external "paddle" or spade balance familiar once again on modern competition aerobatic aircraft.

The 1939-1945 World War II saw intense development of balance techniques for the twin purposes of achieving satisfactory stick feel and stick free static stability. The rapid pace of development under war-time pressure and the inevitable increase in quantity and variety of weapons, fuel load and engine power often resulted in inadequate pitch stability characteristics. By this time a better understanding of critical stability parameters allowed concentration on the stick-free characteristics. These could often be modified by relatively minor changes to elevator balance, avoiding major changes to the overall aircraft weight balance or to the whole tail design to enhance the stick fixed stability. Roll performance, vital to fighter pilots, needed to be improved by lighter stick forces as speeds increased. Hinge moments were reduced by covering control surfaces with metal skins (or even plywood) instead of the fabric usual up to that time. New forms of balance included the Westland-Irving internal sealed balance, anti-balance tab, elevator contouring and trailing edge angle bevelling, and the spring tab. (Smith quotes the chief test pilot for the Vultee Vengeance dive bomber as finding that the spring tab, which he thought he had invented for its rudder, was described in a British patent of around 1916!).

Aerodynamic balance devices were not always sufficient, even assisted by a modest bob-weight as in the case of the Supermarine Spitfire, during the service life of which the weight and power doubled and the centre of gravity range increased from 3% to 11%. Its instability problems were a constant source of worry ("a nightmare", according to a verbal comment to the author by one of the Royal Aeronautical Establishment scientists involved), requiring many detail changes to the tailplane but finally solved fully only by large increases in its tail areas (Quill). Similar difficulties with the North American P-51D Mustang also led to the addition of a bobweight.

By the end of the war, aircraft speeds were reaching well beyond 500 mph, soon to be eclipsed by the new jet aircraft. As control hinge moments became unreasonably large and difficult to alleviate by surface balance, hydraulic power boosted controls became necessary. An early example was on the ailerons of the Lockheed P-38J Lightning. With power boost, some of the aerodynamic hinge moment was felt by the pilot and the control forces stiffened in proportion to dynamic pressure in the conventional manner. In the Supermarine Seafang naval fighter, power boost was used with aileron spring tabs for an impressive rate of roll at high speed. Power boost could not overcome the limitations of elevators at transonic speeds, even with variable incidence follow-up tails. A strong trend to full power was noted already in Dickinson (1953), and full power operation was to be found on all axes in the great majority of the 50 types and variations listed in Lang/Dickinson.

However, the use of power boosted controls had been initiated even before the war in response to the increasing size of some aircraft. The first large aircraft with powered controls was the XB-19 in 1935. The Boeing 307 Stratoliner of 1937 had power boosted rudder and elevator, the component parts being identical to standard brake valves. with manual reversion to control tabs. A Boeing XB-29 was fitted with a trial power boosted rudder, while the more powerful engines on the Boeing B-50 necessitated a fully powered rudder to cope with the engine out cases. The Lockheed Constellation had power boosted controls in all three axes.

Completely artificial feel had become essential with fully powered controls. There was considerable speculation about what elements of "natural feel" should be emulated, coupled with the natural desire to minimise the cost and complexity of the feel devices. The possibilities included control force variation with dynamic pressure (q feel), speed (V feel) or control deflection only (spring feel), also potentially augmented by devices such as bobweights and downsprings which were already familiar on conventional aircraft. The difficulties were compounded by the deterioration in aircraft response qualities due to wing sweep and Mach effects, which could be only partially alleviated by the emerging technology of autostabilisation. However, aircraft designers were never short of ingenuity, and as Dickinson noted, "in particular we can take the opportunity of making control forces do what we desire them to do rather than having to accept the consequences of fundamental laws as hitherto".

As advances in electronic and digital technology advanced towards full fly by wire capability, the mechanical control and feel system complexity reduced once again. Today's stick and feel systems tend to be rather simple in concept, although containing high quality mechanical detail in miniature in their sensor packages.

2.0 AERODYNAMIC FEEL DEVICES

It is not the intention to provide design guidance for aerodynamic feel, a complex subject involving both stability and control, but to draw attention to some salient facts. Only a brief review of the basic characteristics of standard aerodynamic balance devices is given here, taken from Dickinson (1968). More general information can be found in many textbooks (e.g. Dommasch), while the data sheets on Controls and Flaps published by ESDU International contain highly detailed design information, derived mostly from war-time research in the USA and the UK.

The flap type of control, e.g. an elevator, aileron or rudder, is subject to a total hinge moment H, given by $H = C_H \frac{1}{2}\rho V^2 S_\eta c_\eta$, where S_η and c_η are the area and chord of the flap surfaces.

The hinge moment coefficient $C_H = b_0 + b_1\alpha' + b_2\eta + b_3\beta$, where α', η and β are the local angle of attack, the flap deflection from neutral, and the tab deflection from neutral respectively. The b coefficients are generally assumed constant, though this is strictly true only for a limited range of angle of attack and flap deflection. Their values are defined as follows:

- b_0 is the basic moment resulting from flap camber, with zero angle of attack, flap and tab deflections. It is zero for a symmetric section.
- $b_1 = dC_H/d\alpha'$
- $b_2 = dC_H/d\eta$
- $b_3 = dC_H/d\beta$

These factors represent the hinge moment about the flap hinge line. The tab itself has a similar set of moments about its own hinge, the total being given by $C_{Ht} = c_0 + c_1\alpha' + c_2\eta + c_3\beta$. These are significant in the case of the servo tab where the stick is directly connected to the tab.

The dominant factor in stick feel is the "heaviness parameter" b_2, due to control deflection. As the aircraft responds, the stick force may be increased or decreased by the "floating parameter" b_1, due to the changes in local angle of attack, which is accordingly termed the response effect. Defining this effect by

K = *Effort with response / effort without response,*

$$\text{then } K = (b_1 \Delta\alpha' + b_2\Delta\eta)/b_2\Delta\eta$$
$$\text{or } K = 1 + (b_1\Delta\alpha'/b_2\Delta\eta).$$

Noting that the change in angle of attack is of opposite sign to the control deflection, the response effect reduces the stick force if the hinge moment parameters have the same sign. In this case the free control trails with the wind, and in the steady controlled response state it tends to float in the direction in which it is deflected. This is a common condition for a great many aircraft types with little or no special provision for balance, and it does not usually cause any noticeable difficulty.

Elevators that are aerodynamically unbalanced tend to float as the angle of attack changes with speed in the sense to alter the angle of attack still further, reducing the stick force required to hold the new speed and even reversing it if the basic stick-fixed stability is low enough. A shortfall in the provision of latter, determined by the overall geometric and aerodynamic relationships between the wing, tail and centre of gravity, may require a substantial corrective design change. For example, the increase in tail area required to alter the neutral point by a few percent of the mean chord can be surprisingly large, and changing the centre of gravity by a similar amount may simply be impossible. Fortunately, it is widely recognised that even neutral stick-fixed stability, seen as a zero gradient of stick position versus speed, can be acceptable provided that the stick-free stability is positive, seen as a stable stick force gradient with a push force needed to hold an increase of speed. This can be achieved in principle by reversing the sign of the floating parameter b_1, so that the elevator then tends to float against the wind. As an example noted earlier, considerable effort had to be devoted to the task of obtaining sufficient of this effect to keep up with the stability problems of the Spitfire, but many other aircraft have required similar attention.

Thus the stick forces provided by aerodynamic feel means may be influenced by the needs of both control and stability. An excessive float against the wind may reduce the initial control deflection hinge moment considerably, requiring means to increase it. The response effect becomes greater than unity, so that the stick force to hold a manoeuvre is greater than the force to initiate it. Dickinson quotes a proposed maximum value for K of 1·2, but also acknowledges that there is not much practical data to support this. For most purposes it is unlikely that this issue is of significant importance.

By far the greatest problem area for aerodynamic feel is the transonic region and the approach to it. Sometimes fatal steep dives by high powered combat types in the 1939-1945 war were at first attributed to control reversal and thought to be irrecoverable. It was eventually found that recovery would occur at lower altitudes as the Mach Number reduced. The problem was caused by the rearward-shifting wing aerodynamic centre and the reducing effectiveness of flap controls at high Mach Number, producing a strong nose down trim change and leaving little control power to prevent or recover from this. This was of course the driver for the change to power assisted and then fully powered controls.

2.1 The horn balance

This was the earliest balance type, Figure 1, derived from standard boat rudders. They were used on all axes for a time, but Diehl noted that "they are now employed only on rudders and elevators. (They should not) be used on ailerons owing to the poor wing tip and to the high peak loadings on the balanced portion" and "(they) should never be used on high speed designs owing to probability of flutter". Almost without exception, this type is used primarily for its effect on the floating parameter b_1, to enhance the stick free pitch and yaw stabilities. The corresponding reduction in b_2 may also be necessary to reduce the control loads, depending on the size of the tail surfaces and the airspeeds.

A notable exception to these general rules was found in the English Electric P1.A, the prototype of the Lightning fighter of 1954. This Mach 2 design with its unique 60° swept wing with delta-like tips had horn balance on its fully powered ailerons. They were not retained on the production P1.B Lightning as they proved to be unnecessary, but they did not exhibit any of the listed problems either. The Bristol 188 all-steel supersonic research aircraft also had horn balanced ailerons on its sharply raked delta-like tips.

2.2 The set-back hinge balance

Developed quite early, these were first known as the Handley Page balance, Figure 2. The shape of the flap nose, i.e. round, elliptical or blunt, and the closeness of the gap sealing have a strong effect on the values of b_1 and b_2. Once the nose emerges into the airstream, particularly for the blunt nose, the effects may become non-linear. This balance is found on all three control axes. It is frequently employed together with the horn type to achieve sufficient stick free stability, with large reductions in the control forces requiring restoration with anti-balance tabs.

One of the earliest examples was on the elevator of a Levasseur mailplane of 1920, shown in Figure 3. This could actually be termed a mixture of a shielded horn and set-back hinge balance.

2.3 The Westland-Irving sealed balance

This is a modified form of set-back hinge, Figure 4, but is hidden within the surface profile and is therefore particularly suited to high speed aircraft. It is used primarily to reduce control forces, since it has relatively less effect on b_1. The balance is either completely sealed, usually with a flexible strip, or may be adjustable by controlled venting.

It was used both on the ailerons and on the aileron tabs (of the spring tab type) in the manually controlled English Electric Canberra medium jet bomber. There was no sealing strip but the gaps were tightly controlled to about 1 ± ¼ mm. The Avro Vulcan with fully powered controls used this balance type on all axes to reduce the power required.

2.4 Geared tabs

These are a logical development from the basic trim tab, and can be arranged as shown in Figure 5 either to increase or decrease the hinge moments. They have no effect at all on b_1. They can be used as trim tabs as well, by adjusting the length of the actuating rod. This combination can result in extremely large tab deflections relative to the main flap surface at full control travels, and the functions are often confined to separate tabs. Although there is a loss in control lift and effectiveness due to the balance tab, this effect is usually small.

Balance tabs were originally adopted to reduce the hinge moments on larger aircraft. Anti-balance tabs were obviously introduced to increase hinge moments on smaller control surfaces, but they have also been invaluable in rescuing the situation in aircraft in which the stick fixed stability was grossly inadequate through basic design or operational developments. By the time that the stick free stability due to b_1 has been increased sufficiently by means of horn and set-back hinge balance on the elevator, the control moment due to b_2 may have been reduced, eliminated or even reversed. The anti-balance tab allows the control forces to be restored almost to any desired level.

Just as with the main balance forms, hinge line gaps and trailing edge shapes can have serious effects on tab effectiveness. The prototype Airspeed Ambassador twin engine airliner had tabs with sharp-edged riveted trailing edges. The design was changed for production to radiused wrap-around trailing edges, and ceased to work until changed back again.

2.5 Balance by contour modification

Changes to the forward contour of the elevators in the form of a "hump" proved to be a useful method of improving stability, on

the Spitfire and the Vengeance among others. To reduce the flutter prevention mass balancing requirements, control surfaces were fabric covered up to the 1940's. As airspeeds grew rapidly in this period, control forces began to become extremely high, to the extent for example that roll rates were seriously compromised. It was discovered that the outward bulging of the fabric covering modified the b_2 characteristics and could also result in dangerous short period oscillation tendencies.

Metal skins were found to reduce the excessive forces high speed aircraft. This discovery was made fortuitously in the Vultee Vengeance after flutter removed a complete rudder. The ensuing change from the original fabric covering to metal skins on all of its tail control surfaces also eliminated another problem of a nose down pitch at high speeds and excessive stick forces in recovery from dives.

Changes to the trailing edge shape have a pronounced effect on balance, Figure 6, because of the large moment arm from the hinge. The effect of bevelling the trailing edge is to change both b_1 and b_2 considerably, but it may produce non-linear results if this is overdone.

An interesting use of the camber parameter b_0 to enhance stick-free stability is found on many sailplanes without any other form of control balance. The combined effect of a slightly turned down trailing edge on the elevator and a feel spring results in a tendency for the elevator to deflect trailing edge up against the spring restraint as speed increases, requiring the pilot to push harder on the stick even if its position does not change.

2.6 The Frise balance

The adverse yaw due to aileron, a considerable problem on most early aircraft, was to some extent reduced by the use of differential aileron deflection. Loening (1916) optimistically went so far as to suggest that adverse yaw demonstrated careless design, but he was wrong. The invention of the Frise balance, Figure 7, was a further contribution to the solution of this particular problem, and Diehl states that it "is the most satisfactory form of balance now available for ailerons". It has the two characteristics of reducing the hinge moments and of increasing the drag of the up-going aileron, both produced by the action of the leading edge protruding into the lower airstream. Coupled with differential action so that the up travel is much greater than the down, it proved to be very effective.

However, the typical hinge moment variation sketched is extremely non-linear, and no linear value of b_2 can be quoted. The up aileron overbalance which reduces the hinge moment is very sensitive to design, and the combined balance of both ailerons together is also sensitive to rigging tolerances. It is possible for total overbalance to occur over small angles. There may also be some aileron buffet.

This balance was used for example on the Spitfire, Hawker Hurricane and the Avro Lancaster, and has also been used on many smaller general aviation aircraft. Generally, however, it is not suitable for high speed aircraft, and the spring tab replaced it on many combat aircraft. The set back hinge and Irving balance have been more commonly used on larger aircraft.

2.7 The servo tab

The idea of driving a tab alone, Figure 8, using the b_3 moment to deflect the main control surface, was developed in the 1920's as aircraft size increased. The stick forces are small as the pilot has only the tab hinge moment to overcome. The Short Rangoon (1930) and Sarafand (1932) flying boats and the Boulton and Paul Overstrand bomber (1933) used them on their rudders, coupled with horn or set-back hinge balance. Though not widely used, it was successfully employed on all the control surfaces of the four engined turboprop Bristol Britannia airliner and Short Belfast transport. In the latter, a very large aircraft, the system was enhanced by other devices: the elevators had set-back hinges and horn balance to compensate b_1, and the low tab feel forces were increased by a q-feel unit and centring spring; the ailerons had the Irving balance with a spring to resist up-float; the rudder control had a feel spring and the tab had a blow-off spring incorporated to reduce its power at high speeds. The original BAC 111 prototype jet airliner had a servo tab elevator, but this was replaced by power operation after loss of control in deep stalls.

2.8 The spring tab

This is a modified servo tab in which the pilot's input drives the tab directly, as before, but is also connected indirectly to the main control surface through a spring (usually a torsion spring), Figure 9. At very low speeds the spring acts as a rigid link since the hinge moments are negligible. As speed and the effect of b_2 increase, the spring deflects more and more so that the tab deflects relative to the main control surface by increasing amounts, relieving the main surface hinge moment. The result is effectively a value of b_2 which varies by the factor $1/(1 + kq)$, where q is the dynamic pressure, and k is a function of the spring link stiffness and tab gearing. The sketches showing the typical effects of spring tabs on hinge moments and stick force per g indicate that the type was basically most suited to aileron control. A moment variation effectively more proportional to V rather than to V^2 can be achieved which gives nominally constant roll rate per unit stick force.

Unlike other balance types, over-balance is impossible because control force in the correct direction is always required to produce some tab deflection. However, if the gain k is too large or the range of dynamic pressure too wide, the result can be excessive lightening at high speeds. The blow-off spring tab was developed to prevent this, by means of a spring in the tab linkage which reduces the tab deflections as its hinge moments increase. This opened up the use of the tab to the other two axes, nominally requiring q (or V^2) feel but where high speed aeroelastic or Mach number effects could lead to excessive control heaviness. The ability to tune the hinge moments to some power of V less than 2 enabled these high forces to be alleviated.

Control system stretch due to large hinge moments and the resulting reduction in maximum aileron angle was a common cause of reduced roll performance, in addition to the normal aeroelastic losses due to structural deformation of the wing and aileron. Such losses have sometimes been relied upon to satisfy maximum stressing cases such as the rolling pull-out. Adoption of spring tabs on the Hawker Tempest V tactical and battlefield support fighter of 1944/45 gave exceptionally good aileron control and performance at speeds of over 500 miles per hour, but also gave some concern about wing strength due to the larger aileron angles which could be applied.

Other aircraft with spring tabs which have demonstrated high agility include the Martin Baker MB.5 prototype (possibly the fastest ever piston engined fighter but which was overtaken by the jet era), and the English Electric Canberra jet bomber, both of which used these tabs on all three axes. In the Canberra the blow-off type was used, the main and blow-off springs being co-axial torsion tubes and rods, and a geared tab was also used on the elevator. The FIAT G.222 twin turboprop military transport, with spring tab ailerons, could readily perform single-engine 360° rolls.

A completely different requirement arose on the Vultee Vengeance dive bomber, with which British, Australian and Indian squadrons achieved devastatingly accurate strikes with negligible losses in the New Guinea and Burma campaigns of 1943 and 1944. Designed for vertical attacks, achievement of the required precise alignment of the fuselage with the target necessitated light and accurate rudder control, so that the directional trim changes between climb and diving speeds could be countered without having to adjust the trimmer. This was achieved successfully by the adoption of a spring tab on the rudder to augment the set-back hinge balance.

2.9 Tab systems design

The many similar mechanical features of the basic tab concepts and the essentially small design differences between them are illustrated in Figure 10, based on the elevator balance and aileron spring tabs of the FIAT G.222. The range of characteristics of balance and stability effects is extremely wide, development being aided by the relative simplicity of making gearing changes.

Geared anti-balance tabs are practically an essential feature of manually operated all-flying tails. The dangerous behaviour of the Morane Parasol with its plain all-moving tail was mentioned earlier, and the Fokker E-III was another type with unpleasant handling because of its similar tail. It was also used on a few early sailplane designs of the 1930's, where the low flying speeds enabled more or less acceptable hands-on control. In the Slingsby Petrel, the stick was very long with a large travel, and the lack of stick force was scarcely noticed, but the design was changed to a tail and elevator. More recently, some racing sailplanes returned to the plain flying tail with additional spring feel, but their wide speed range made for very low stick force per g at high speeds where it was advisable to fly them with both hands on the stick. Such a design is no longer tolerated.

The design of a maually operated all-flying tail and its control forces is closely associated with the stick free stability characteristics. This subject is examined by Irving for the case of linear low-speed assumptions with no Mach Number or aeroelastic effects. With the tail pivoted at its aerodynamic centre, b_1 and b_2 are zero. Hence there is no loss in stick free stability relative to the stick fixed value, a bonus point, but there is no stick force either. The addition of an anti-balance tab achieves the required b_2. Trimming in this arrangement is invariably done by adjusting the geared tab position, since the trimmed state always requires zero tab deflection or nearly so. By placing the pivot aft of the aerodynamic centre, a positive b_1 can be obtained with enhanced stick-free stability. The divergent hinge moments resulting from this are opposed by the stable hinge moments due to the tab, and extremely wide variations of the two parameters can be readily obtained.

Such a tail is not suited to large aircraft, however, as it becomes increasingly difficult to ensure adequate control of the hinge moments as unavoidable non-linear effects become more significant. The necessity to prevent flutter by mass balance to bring the tail centre of gravity to the pivot axis introduces a substantial weight penalty. Probably the largest type to have used it is the GAF Nomad twin turboprop, and this did require some significant development effort.

2.10 Mechanical aids

Shortfalls in aerodynamic static and manoeuvre stick force characteristics have been addressed in many designs by the use of bobweights and downsprings as sketched in Figure 11. A bobweight, which is an inertia weight attached to the control system so as to pull the stick forwards with increasing normal acceleration, increases the stick force per g by a constant increment. A downspring, attached to the control system so as to pull the stick forwards, increases the stick free stability. The latter effect is seen as an increasing aft stick force to resist the spring pull as speed decreases below that at which the elevator trim tab balances the spring. The principle requires the use of a "long spring", effectively with zero rate so as to apply a constant force. A bobweight without a counter-balance spring also acts as a downspring. Most low speed aircraft without mass balanced elevators, i.e. the majority in the earlier decades of aviation, effectively had a built-in bobweight and downspring, usually without any adverse consequences. However, although the steady state effects are readily obtained, the dynamic stability of downspring and bobweight systems can be troublesome, with undesirable handling effects due to couplings into the short period and phugoid oscillation modes.

A number of attempts were made in the 1939-1945 war to obtain moderate and reasonably constant stick force per g by very close balancing of the elevators, i.e. with small or zero b_2, and providing most or all the force by means of a bobweight. This subject is dealt with comprehensively in the BIUG to Mil. Spec. 8785B, illustrated by the example of the P-63A-1 with a 3·7 lb/g bobweight. Although the steady state variations of stick force were satisfactory, the "response feel" was unacceptable because the initial control movement required little or no stick force and the required input was therefore unpredictable. The controllability was improved by the addition of a feel spring, which provided a force cue without the lag in the bobweight force feedback. The same problems were found on other aircraft at that time.

The North American P-51 Mustang fighter suffered serious loss of stability as it was stretched to the P-51D version with an aft fuselage fuel tank and additional equipment. Its pilot's manual cautioned that with this tank full the aircraft was unstable and could not be trimmed for hands-off level flight, and it was necessary to push forward in turns or pullouts. Acrobatics were prohibited with more than 40 gallons of fuel. This problem was alleviated by the addition of a 20 lb bobweight, although in some cases even this only reduced the forward push necessary.

The Supermarine Spitfire, its instability problems also compounded by extra aft fuel or equipment, acquired a 3 lb/g bobweight after the sudden discovery that many were seriously unstable, which was thought to explain a number of wing failures. Although the bobweight improved the situation significantly, Crossley describes several shortcomings of the device in the naval version, the Seafire. Many Seafires, with aft arrester hook, extra camera gear, and some with heavier gauge fuselage skinning, were still more unstable and were outside the CG limits for the bobweight. A number of wings were broken off or damaged in dive recoveries, and this was eventually attributed to the position of the bobweight and to the use of a balance spring to counter the bobweight in level flight. Figure 12 shows the effects of attitude. In a steep dive, e.g. in the Seafire's very successful yo-yo attacks employed against the A6M Zeke, the bobweight no longer generated a stick force but the spring remained active, pulling the stick aft. With no time to re-trim, when the pull-out was made it was all too easy to apply excessive stick input, and excessive g could result.

Bailing out of the Seafire from the recommended inverted position after engine failure was apparently never successfully achieved. In this case, both bobweight and balance spring pulled the stick aft, which could not be trimmed out, and so when left to its own devices the aircraft would go into the second half of a loop, while the pilot with harness undone could neither reach the stick nor get out. The naval Fairey Firefly two-seat attack aircraft had its bobweight mounted as in Figure 13 and had no balance spring, preventing any such problem. However, there are always two flight attitudes in which the bobweight applies no force in steady flight conditions.

Bobweights continued to be used on many manually controlled aircraft of many types, e.g. the piston engined Hunting Provost trainer, some marks of the de Havilland Vampire and the four engined de Havilland/British Aerospace 146. Downsprings have been used in a great many aircraft of all shapes and sizes, e.g. from the early de Havilland Vampire jet fighter, where it comprised a bungee cord stretched the full length of a tail boom, the Handley Page Hastings four engined military transport, and many general aviation aircraft. In the Fokker F27 Friendship twin turboprop airliner, the downspring applies a force of 14·5 kg to the stick, which according to van der Vaart (1983) requires an incremental trim tab deflection of nearly 10° at the relatively low sea level airspeed of 70 m/sec. In this case the nett angle was about zero, but the inference is clear that the amount of additional stick force that can sensibly be added by a downspring is limited by the ability to trim it with reasonable tab deflections.

The BIUG cautions against the possibility of trading a statically unstable aircraft for a dynamically unstable one by the use of too strong a downspring, examples of this being found in Gold-

berg and in Barber. Goldberg and Auterson/Lyon analyse the effects of these devices, both assuming the so-called "long spring". Eshelby analysed the effects of using a short spring, i.e. one with a significant stiffness, and found that it can have undesirable effects. Constant rate springs are available, however, such as the "Tensator" type formed from coiled spring steel flat strip, which should be well suited for this purpose.

The heavy ailerons on the North American Mustang necessitated a very large lateral stick travel of some ±8 inches. Some later versions had a gear change device at the base of the column, which with the tab system gave very satisfactory control.

Mechanical aids of many types can be extremely useful, but great care is needed not to try to use some of them beyond practical limits.

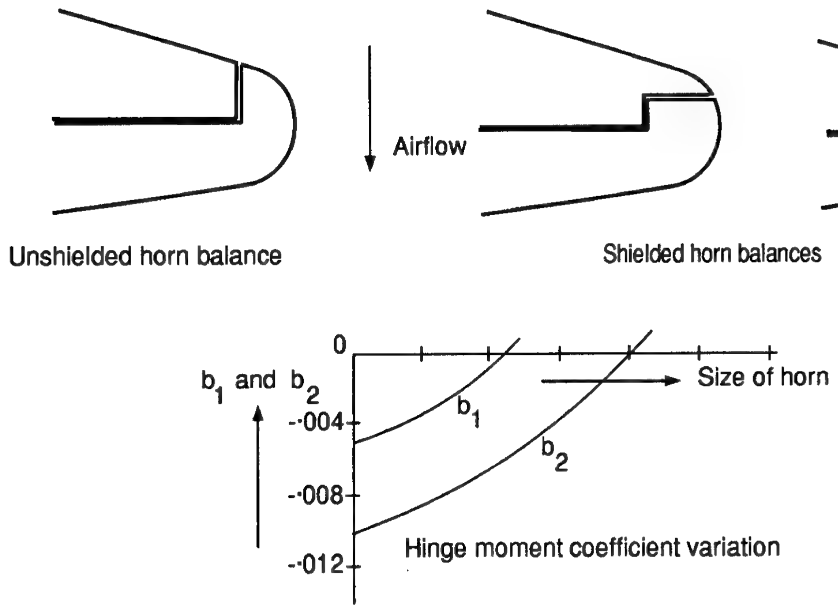


Figure 1 The horn balance

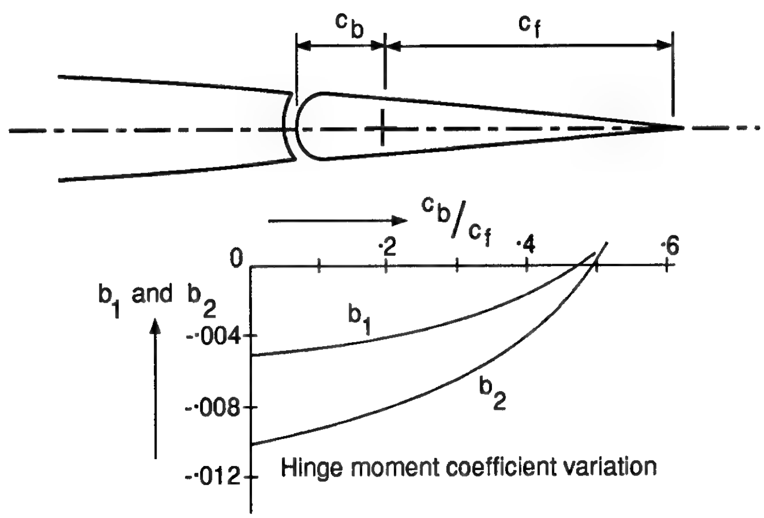


Figure 2 The set-back hinge

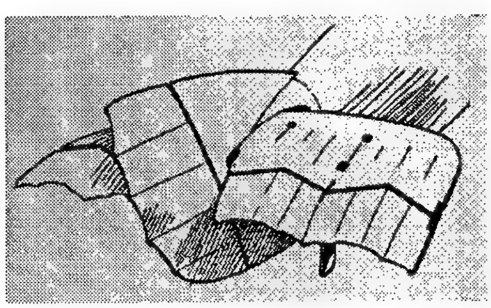


Figure 3 Levasseur semi-horn set-back hinge, 1920

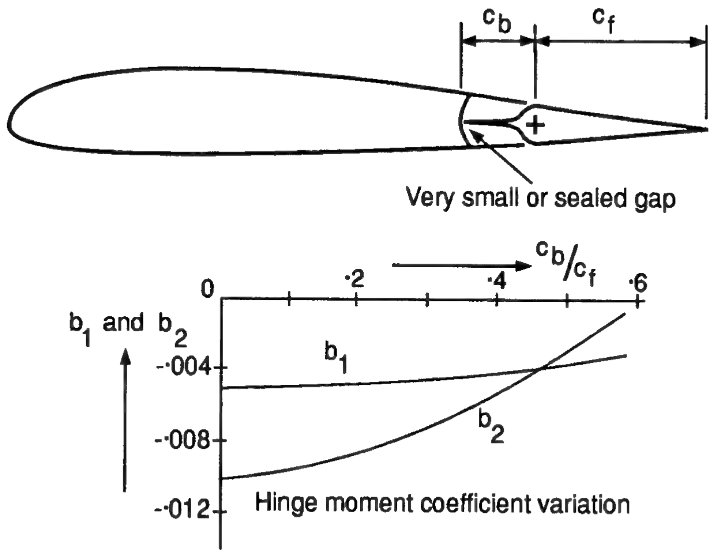


Figure 4 The Westland-Irving internal balance

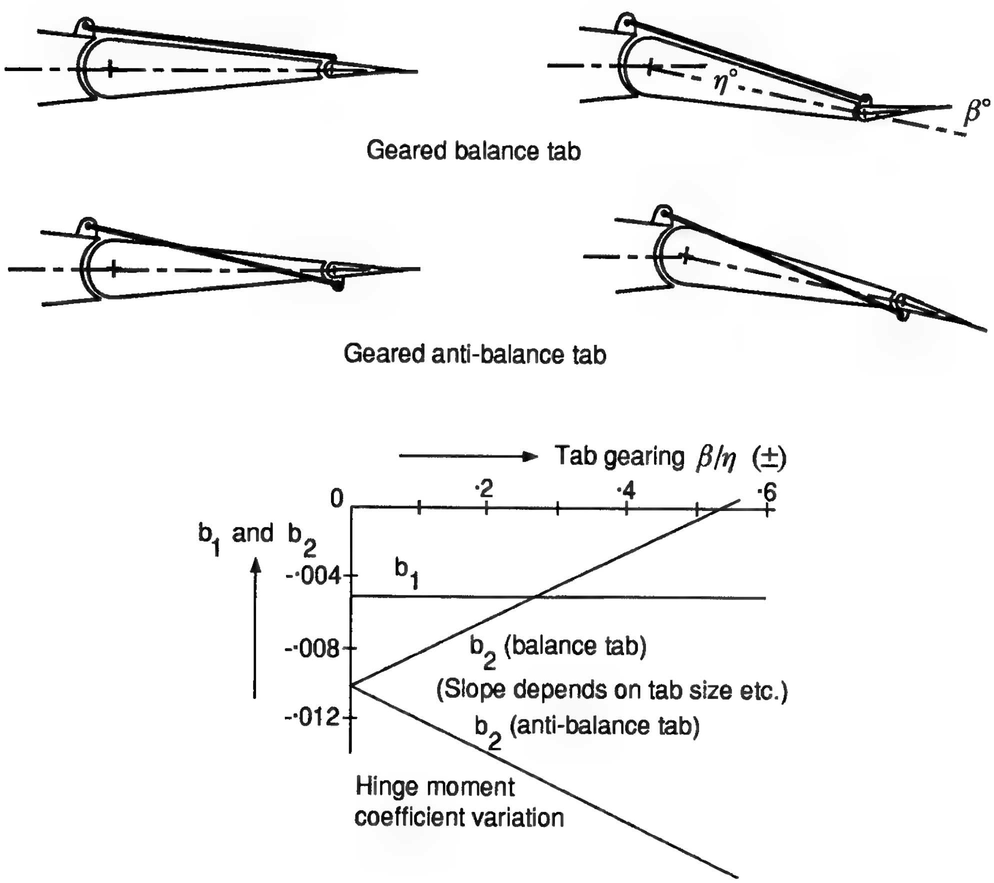


Figure 5 Balance and anti-balance tabs

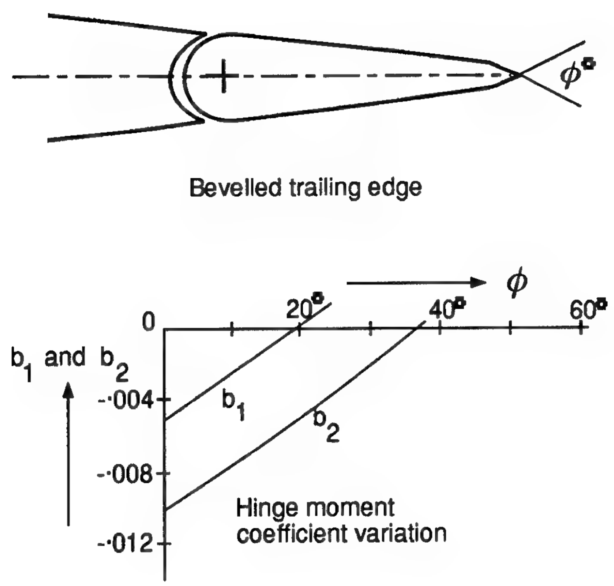


Figure 6 Profile shape modification

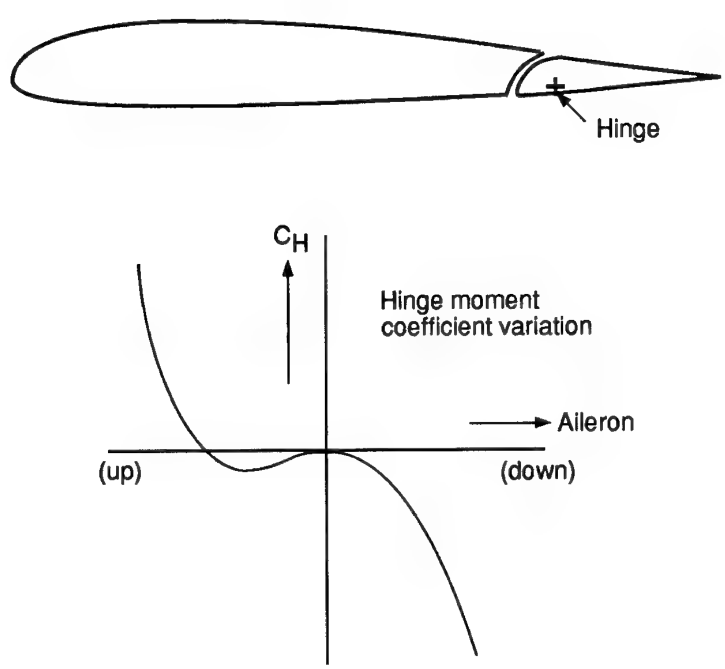
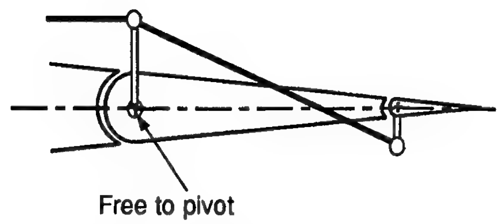
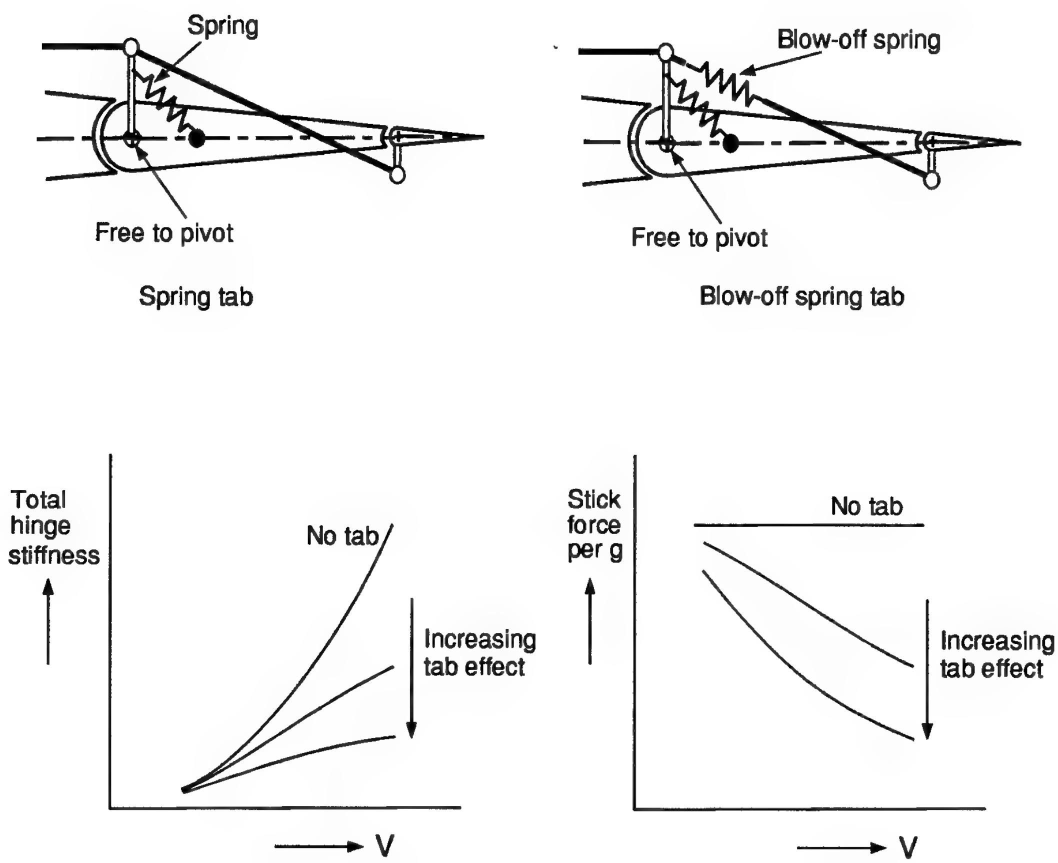


Figure 7 The Frise aileron



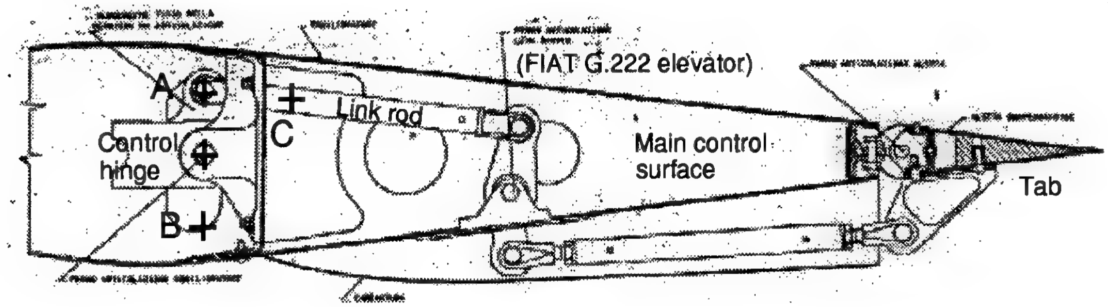
Elevator angle = $-b_3/b_2$ x tab angle

Figure 8 The servo tab

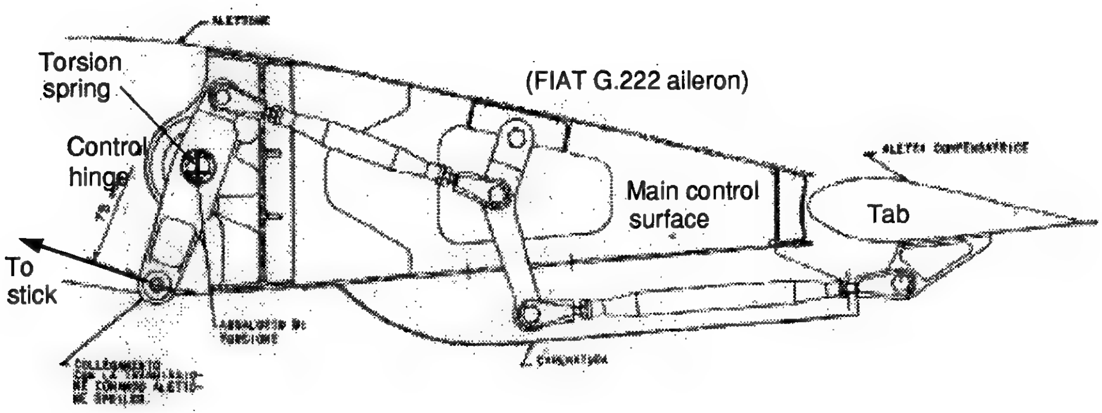


Spring tab effects

Figure 9 The spring tab system



Balance tab: link rod attached at A
Anti-balance tab: link rod attached at B
Trim tab: link rod adjustable (e.g. electric screwjack) and attached at C
Combined trim and balance/anti-balance tab: link rod adjustable and attached at A or B



Servo tab: input lever free to pivot at control hinge line
Spring tab: input lever connected to main control surface by torsion shaft

Figure 10 Tab variations built on common features

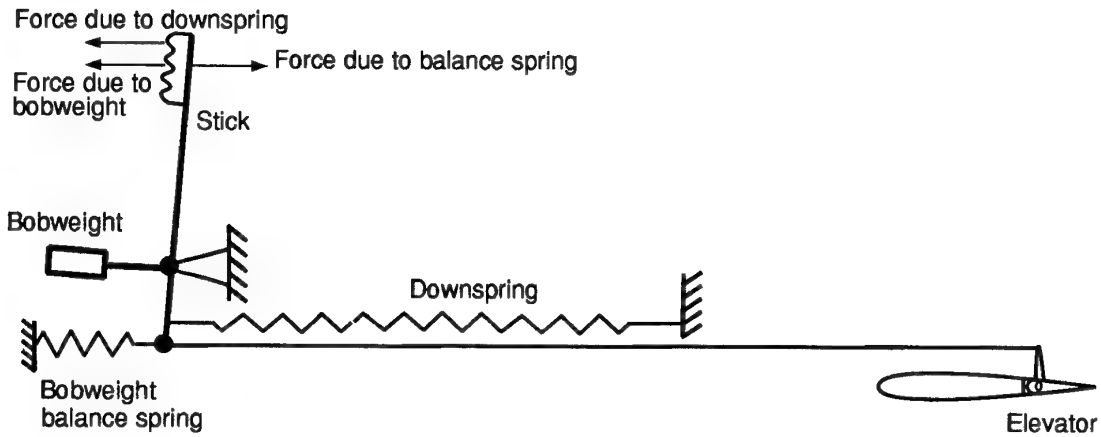


Figure 11 Mechanical aids to aerodynamic balance

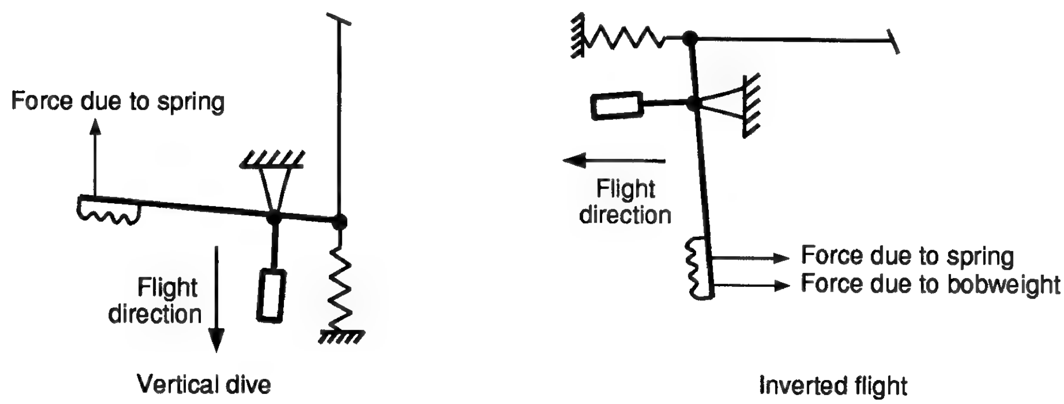


Figure 12 Effects of attitude on bobweight and spring balance forces

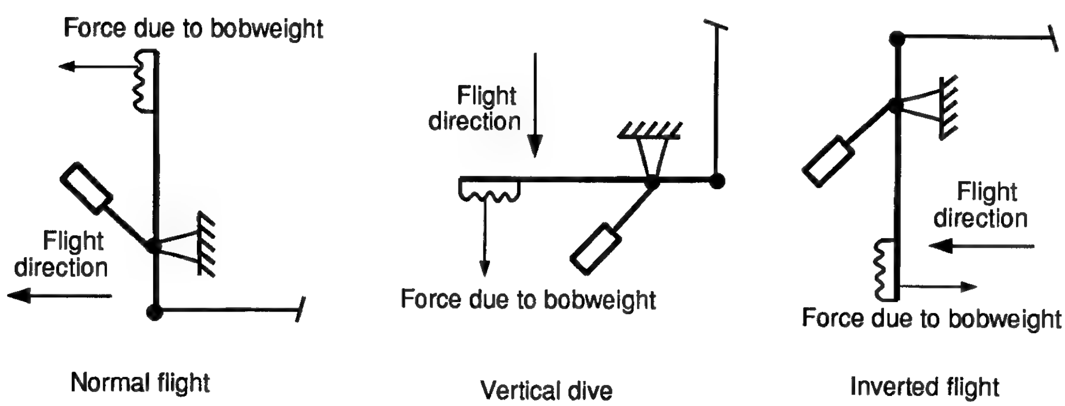


Figure 13 Alternative bobweight arrangement

3.0 POWERED CONTROL SYSTEMS.

Adopted for the purpose of isolating the pilot from the aerodynamic hinge moments, hydraulic control surface power actuators also eliminated the dominant control system damping effects, introduced additional effects due to valve friction and flow forces, and increased the importance of the contribution to the feel characteristics of the "control circuits" themselves. This term has been widely used for the mechanical connections between the stick or pedals and the control surfaces, or their actuators, in which context it has nothing to do with electrical or electronic circuits. They were originally in the form of flexible wires or cables strung around pulleys or between levers, but push-pull rod systems also became widely used. There are arguments for and against either form, and the design choice has also sometimes been a matter of custom and practice. Effects of friction have always intruded on the feel qualities, more easily minimised in push rod systems, but on the other hand the effects of inertial mass or balancing are more significant in the latter.

Figure 14 shows a generalised power control system schematic illustrated in McRuer (1975). This contains most of the elements typically found in the pitch axis feel systems of 1950's and 1960's aircraft, and some are still in use today. Many systems were of the spring plus bobweight type shown, but a number replicated the normal aerodynamic characteristic of hinge moments proportional to dynamic pressure by the use of q-feel without bobweights. Small-authority single channel stability augmentation was applied by limited-travel series servo actuators, summing their inputs mechanically with those of the pilot. In the roll axis, the simple spring feel was almost universal. In the yaw axis, q-feel was often used, but spring feel with variable gearing or limit stops was also popular and has occasionally been used in the pitch axis.

3.1 Power control actuation

A brief survey of the characteristics of power boost actuation is given. It is unlikely that this system will be used again in the future, but the lessons should not be forgotten. Most of its problems disappeared with the adoption of full power actuation, but in its turn the latter had characteristics which were frequently unsatisfactory and became all the more apparent when the major aerodynamic-related difficulties were eliminated.

3.1.1 Power boost control

The surface actuator in Figure 14 is actually of the power boost type, the earliest form of power control which soon went out of favour, but is retained here for completeness. Figure 15 shows the principle of operation. Except for the transient valve movements necessary to port fluid to and from the cylinder, the actuator body maintains an essentially constant length between its attachment to the surface and the valve input link. Hence the surface moves as if directly connected through this path. The force generated by the surface hinge moment is reflected into the control circuit through the body, fluid pressure and ram path, the ram extension automatically accommodating the difference between the movements of the valve link and ram connections to the input lever. Hence the force felt by the pilot can be adjusted by any desired ratio relative to a direct connection. This force is still proportional to the hinge moment, however, and no artificial feel device is required.

When the pilot moves the controls, the valve is initially closed and cannot open until there has been some displacement of the system. This would imply that the full force must first be exerted on the surface through the ram and actuator body until relieved by the valve opening, but in practice there seems to have been sufficient compliance in the mechanisms to avoid much difficulty of this nature. The power boosted ailerons of the Blackburn Firebrand, which were not excessively heavy and were an improvement over the original spring tabs, did require a large force to apply the continual small deflections to correct for bumps in rough weather, which was tiring in prolonged turbulence. On the other hand, the North American F-86A power boosted ailerons, though exceptionally light and powerful in general, lacked feel at low speeds, did not centre well and suffered from a lateral wobble attributed not so much to the light forces as to the power boost cutting in suddenly in response to small aileron movements. On the Gloster Javelin, the large ailerons with rather low boost ratio were completely unacceptable at high speeds, becoming almost solid at 500 knots. The combination of power boost and spring tab ailerons gave excellent control on the Supermarine Seafang and Swift.

Power boosted elevators generally seemed to perform quite well at subsonic speeds, but were deficient at transonic speeds. Despite a boost ratio of 40:1, the F-86A required a push force of about 100 lbs to hold the nose up trim change which occurred at around Mach 1·0, and as on many such aircraft much use was made of the electrically operated variable incidence tailplane to assist in general manoeuvres. The prototype de Havilland DH.110 elevator had a pilot-variable boost ratio between 70:1 and 5:1 with spring feel centring. It had very light manoeuvring stick forces but high circuit breakout, a very unsatisfactory combination, which could be alleviated by reducing the boost ratio only at the expense of heavy manoeuvring forces at high speeds and critical Mach numbers.

These actuators invariably operated on a single hydraulic supply, with reversion to direct manual operation after hydraulic failure. This meant that control was effected through the backlash associated with the valve stroke limits, the cylinder fluid being ported to flow freely from chamber to chamber. It was typically required that the backlash should be not more than 2° of surface deflection. The manual reversion stick forces became very high and were exacerbated by actuator seal friction. The boosted spring tabs of the Swift elevator and ailerons were highly appreciated for the fact that reversionary control was still quite reasonable. On the DH.110, the aileron gearing could be selected to half authority to make control easier after manual reversion.

By the early 1950's it was already confirmed that power boosted controls would not allow the full potential of the new high performance aircraft to be realised. Either the stick forces were satisfactory at low and moderate speeds but became excessive at high speeds and Mach numbers, or if satisfactory at the latter conditions the forces were too low at low speeds. Interestingly, it was once suggested that of the two possible alternatives of full power control or a variable boost ratio equivalent almost to full power control at high speeds, the latter might be preferable as the simplest, but full power control rapidly became the norm.

3.1.2 Full power control

If the actuator ram pivot on the input lever in Figure 15 is moved down to coincide with the lever pivot point, the control surface becomes fully powered, and the only forces felt by the pilot are due to the valve system. This arrangement was commonly reversed, with the actuator body pivoted on the structure and the ram connected to the surface. This avoids significant movements of the hydraulic supply pipes, other than the unavoidable small swing angles, and of the electrical connections to the servo actuators which became more usually mounted on the power actuator rather than separately in the control circuit. The ram and input motions are then differenced to drive the valve by actuator-mounted summing linkage.

Although actuator stability is outside the scope of this report, it can have an influence on the feel characteristics. A tendency to instability arises when an output mass is attached, from the fact that an external force applied to the actuator causes attachment deflections which open the valve to resist, feeding energy into the system. If the mass is not excessive, the case with many flap type controls, the damping due to actuator seal friction can be sufficient to avoid instability. This problem is avoided by alternatives of an arrangement of the input linkage, by a system of

pressure sensing valves, or by electrical feedback shaping, which bleed energy from the system by causing the actuator to sink under load, reducing the static stiffness.

An unusual effect occurs on the Sepecat Jaguar at transonic speeds, to an extent dependent on the engine version fitted. Its tail configuration is subject to hinge moment variations as a function of thrust or afterburning state, causing a change in trim as the thrust is varied. Because the pitch axis incorporates a markedly non-linear stick gearing, the resulting stick deflection required to maintain undisturbed flight is much larger than would be the case with a linear system, though it is not hazardous. Actuator sink can prevented by washout methods in the second and third stabilising devices listed above, to maintain high static stiffness with reduced dynamic stiffness.

Figure 16 illustrates some important effects associated with the actuator valves:

- Special valve spool shaping minimises the flow force exerted on the valve. which is proportional to the flow velocity, but it cannot be eliminated altogether. The effect is that of a viscous damper in the control circuit, and is satisfactory if there is not too much of it.
- Significant valve friction is a serious defect, tending to prevent the natural self centring by holding the valve open. The control surface and control circuit are effectively locked together in this state, causing undemanded movements until there is sufficient resistance from the feel spring stiffness, breakout forces or circuit friction.
- Valve springs can be used to improve centring. Alternatively, if these are unbalanced or if only one is used, a nominally constant force is applied to the control circuit which helps to load out any backlash in it.

The BAC TSR-2 of the early 1960's had two tailplane actuators of some 27 tonnes thrust each. The valve flow forces produced greatly excessive stick damping, and a two-spool design was adopted. A small pilot valve, driven directly by the control circuit, resided within and drove the main power spool (with a loop gain of 1200 $secs^{-1}$, there was negligible influence on performance). This entirely eliminated the damping effect, but the control circuit, with considerable inertia from its 25 metres length and with extremely low friction and breakout force, was insufficiently damped with its relatively low natural frequency. A dedicated viscous damper had to be added.

The valve travel limits are usually no greater than required to achieve maximum actuator rate. If the input linkage is moved faster than this in a stick snatch, the valve bottoms and is felt as a resistance at the stick. (In power boost systems, this could be felt as a loss of boost.) In the English Electric Lightning single seat interceptor, the maximum aileron actuator rate was 160°/sec, and with only $\pm$ 8 degrees of aileron with wheels up it was effectively impossible to bottom the valves. Its all-moving tail was driven by a screwjack actuator with a 35°/sec maximum rate, a factor used in a pre-flight check of the hydraulics supply. With the engines at idle, the stick was stroked rapidly from end to end until the valve bottomed, at which point the stick rate was forcibly reduced. The number of strokes required to reach this condition indicated the state of the hydraulic acccumulator, a device often relied on to provide high transient flow at a rate higher than the basic capacity of the pump on its own.

3.2 Control circuit considerations

Many alternative arrangements of the control circuits are possible other than the schematic of Figure 14, but it serves as a basis for discussion of many design considerations influencing the feel characteristics.

3.2.1 The series servo

The series servo was used to effect stability augmentation and sometimes autopilot commands. These are applied to the actuator by summation of its output with the pilot's linkage motions by a summing lever. There is nothing explicit in this arrangement to indicate in which direction the summed motion should travel, however. It relies on the upstream impedance of the stick and feel system being greater than the downstream impedance of the valve linkage and forces. For this reason it was typically located as near to the actuator as possible, ultimately migrating to the actuator itself on many designs. In the latter location it could also readily perform a second function of a full authority parallel autopilot actuator with the input linkage clutched to the power actuator. Motions of the ram then drove the entire circuit linkage and stick to follow the surface position. Such a system was developed in the 1960's for the pitch axis of the English Electric/BAC Lightning, in a radar-guided air-to-air missile supersonic auto-attack mode. Although highly successful, the system was not adopted for production. It was employed in the pitch axis autopilot of the BAC TSR-2.

These requirements impacted on the feel characteristics by requiring sufficiently positive control circuit centring and breakout forces. The feel unit breakout force would normally have been determined by the perceived need for positive centring of the whole control circuit, but it also performed the duty of a high impedance point against which the series servo could work. A spring loaded roller-cam device of the type suggested in Figure 14 was commonly used to provide positive breakout as well as a force gradient which could be shaped to any desired linear or non-linear form.

3.2.2 Feel unit location

Backlash at the stick without stick force or a corresponding control response does not cause significant problems if there is not too much of it. Backlash between the feel unit and the surface actuator creates indeterminate positioning of the surface, which can be very undesirable especially in high speed conditions with high control sensitivity. Backlash between the circuit and feel unit but with none between the stick and control surface is unacceptable, since control demands can be made without a corresponding stick force. Such considerations suggest that the best place in which to locate feel units is as near to the actuator as possible. This location also minimises the backlash or compliance which would cause lost motion in the servo signals to the power actuator.

Most aircraft probably did use such a location as suggested in Figure 14. The Lightning was one, but the TSR-2 from the same stable placed the feel units at the stick. The reason for this was that the push rod circuits were very long, about 25 metres between stick and actuators. The feel loads exerted on them would have increased the friction, contrary to the extreme importance attached to minimising friction for the primary task including very high speed ground-level operation with a design limit of 800 knots. To prevent backlash in the unloaded parts of the circuits, the actuator valve bias spring shown in Figure 16 was used, and the bias force was counter-balanced by Tensator constant force springs in the control circuits. The Sepecat Jaguar, with its pitch feel unit at the stick, also used a valve bias spring, but without a counter-balance. Figure 17 shows typical valve forces, comprising a flow force tolerance and the spring bias. The pitch non-linear gearing resulted in a widely varying incremental stick force due to the valve springs as the stick position changed, but this was quite small for the majority of important flight conditions including its primary role of high speed operations at down to 100 feet altitude. No adverse comments were made about the lack of bias balance.

3.2.3 Mechanical qualities

The experience of Service assessments of many types recorded by Lang/Dickinson (1961) was that a large part of the serious

control difficulties encountered in many of them could be attributed to the effects of friction. There was always an improvement in control characteristics when a reduction in friction was made, and there was no evidence that friction could be too small. Aircraft in which the friction was well under 1 lb had very precise control, and it was suggested that an upper limit of 1 lb for air to air and air to ground aiming tasks should be set. The breakout force is due to friction and to any spring pre-load, typically as sketched in Figure 18. Depending on the amount and type of the circuit loaded by feel forces, the friction hysteresis increases with greater deflection. In cable circuits the hysteresis loop width could be 5 to 15 lbs, or even 20 to 40 lbs particularly in rudder controls. Sufficient spring preload would normally be used to achieve adequate centring, Figure 18b. Friction effects also include "stiction" requiring a larger force to initiate movement than to keep it moving against friction. Pilots objected to large breakout on the more manoeuvrable types.

While adequate self-centring was desirable to assist in trimming, it was unclear how positive this needed to be. It was found that pilots of fighters and attack aircraft appeared to prefer small breakout even if the self-centring was not absolute. Bird concluded that reducing friction was the most important parameter for control in the small stick deflection area, and that for a given friction the addition of preload did not improve the handling qualities. On bombers and transports required to cruise for long periods, positive self-centring was more desirable, and even the effects of very high friction and breakout could be tolerated by the expedient of "flying on the trimmer". This was thought to be highly undesirable and possibly dangerous.

The two standard methods of transmitting stick signals to the actuators are the cable circuit and the push rod circuit. With entirely different mechanical properties, each has its devotees.

- Cables have negligible inertia or backlash, and they can follow tortuous paths through small confines if necessary. They are easy to seal at pressure bulkheads. Because they need to be kept under considerable tension to minimise compliance due to stretch, cable circuits tend to have relatively high friction unless of particularly simple layout, and every bend around a pulley or through a fairlead adds to the friction. Significant maintenance effort is often necessary.
- Push rod circuits have low inherent friction because they are mounted on levers with low friction bearings and with no basic loading. They can alternatively pass through confined areas suspended in roller bearing supports. They may have considerable inertia and require balancing masses to eliminate unwanted response feedback to the stick. Even with precision bearings, every rod joint adds to the total backlash (although this can be loaded out by a valve bias spring as above).

Figure 19 shows the Lockheed SR-71 elevon cable control system, working in an extreme environment where fuselage heating causes substantial changes in fuselage length. This is compensated by tension regulators allowing the effective cable length to alter without a change in tension. The cables run in numerous fairleads within dry tubes through the forward and aft fuel tanks, pre-assembled and drawn into place by a locating cable. The pitch and roll signals are mixed at the extreme rear of the aircraft, continuing to the multiple actuators in push rod form. Despite the relatively straight cable runs, the friction levels are quite substantial. The mixer unit performs the function of an anchor point to react the triple redundant stability augmentation servos in the wings, and to permit smooth functioning of the manual and Mach series trimmers contained with the feel springs in the mixer.

Choice of rod travels is influenced by opposing needs, to minimise it for minimum inertia and to maximise it to reduce the relative value of the absolute backlash at the joints. Total travels of 100 to 125 mm have worked well in both regards. On the TSR-2, before the valve bias anti-backlash spring solution was adopted, a 200 mm total pitch circuit travel was chosen because of its severe demands on precision, but as a given push rod mass reflects its inertia to the stick in proportion to the square of its travel, the inertia was large. In practice, no problems were experienced once the viscous damping was optimised. In addition, the reflected inertia was reduced by a non-linear stick gearing in the task-critical high speed low altitude conditions, where the handling was rated as excellent even without autostabilisation.

Some idea of the scale of possible contributions to the feel qualities of control circuits may be gained from the British Aerospace Hawk and the VFW VAK-191B circuits. The Hawk system, Figure 20, is about as simple and direct as is possible with push rods suspended on levers. The relatively short travel ensures low inertia and friction. The pitch non-linear gearing lies at the extreme aft end of the system, so there is no variation of the mechanical qualities with stick position. The original two seat trainer had a manual rudder with no artificial feel, a power control with a yaw damper being added in the more recent single seat version shown here. Even with a pitch bobweight, no viscous damper was fitted prior to the T-45 Goshawk version. The precision of control is famously exhibited by the Red Arrows aerobatic team of the Royal Air Force.

The VAK-191B, a prototype VTOL strike aircraft, had full authority stability augmentation, a reaction nozzle control system, and mechanical reversion, Figure 21. The complexity of this was driven by the need to perform hovering or rolling vertical landings, the minimum conventional approach speed being over 200 knots. The control circuit employed push rods and cables, and the front and rear reaction nozzles were connected by a torque shaft, in which excess friction is difficult to avoid because the drive is geared up to minimise compliance in the long thin shafts. In mechanical mode, hover control was considered unsafe for landing, based on a hovering rig and piloted simulation, because of the excessive backlash and large friction breakout and force gradients of the entire system. Since it was only there for the reversion case, the mechanical system served no useful function. The design was not developed, and there was no opportunity to correct these deficiencies.

Holladay discusses the flight controls influence on VTOL aircraft. This shows how control circuit elasticity, friction and inertia must be analysed as well as the gyros, stabilisers etc. It comments that cable systems had been found to be poor, with 180° phase lag possible at low frequencies.

An example of an aircraft with precise control qualities mentioned by Lang/Dickinson was the English Electric Lightning from 1954, Figure 22. The friction in its pushrod circuits was generally about 0·5 to 0·75 lbs (2 to 3 N). Although spring preload breakout devices were originally fitted to the prototype linear gradient feel units, these were removed almost at once when flight testing commenced. No autostabilisation was fitted during the first four years of development, nor was any thought necessary by the pilots over its entire subsonic and supersonic envelope. (After its fitment, however, the pilots raised the level of their expectations, a common experience in the improving art and science of flight control design.)

The problem of excessive friction has sometimes been overcome by the use of small hydraulic servo actuators to drive the control circuits, so that only the valve forces are felt at the stick. Some examples are the Lockheed C-5A, the Boeing 747 and 767 aileron/spoiler system, and the ailerons of a fighter listed in Lang/Dickinson.

The stick forces due to artificial feel forces are generally much lower than those due to the high hinge moments of unpowered surfaces which often caused significant loss of control effectiveness through circuit stretch. This is therefore less of a problem, though it cannot be neglected. This effect can influence the choice of where to place the travel stops. The ideal location is at the stick, where the design stress loads applied to the stick

or pedals can be reacted while subjecting the rest of the circuit only to the usually much lower operating loads up to the feel unit. If these loads are large and the circuits are long, some loss of maximum signal will occur. This is only likely to be significant with a q-feel system, but here the implication would be of high speeds where large control travels must not be applied in any case and where the stops would not be reached.

3.2.4 Trimming methods

Two basic trimming methods with different transient effects on the handling may be used to remove an out of trim force being held on the stick. In parallel or feel trimming, the stick position is held fixed while the feel unit is repositioned to reduce the force to zero. In series or datum trimming, the stick zero force position is fixed and the stick is returned to it while the trim actuator alters the datum of the pitch control, either by altering the length of the control circuit or by resetting a trimming tail. These are illustrated schematically in Figure 23. Series trimming is naturally used widely on transport and other aircraft which tend to have trimming tails and which normally operate in long periods of cruising flight. On aircraft which are frequently manoeuvred and require to be retrimmed often, pilots greatly prefer parallel trimming. Series trimming is more difficult to use while setting a new trim condition and holding the flight path steady, and the stick movements can seem unnatural in a take-off acceleration and climb-out.

The ease of trimming is more generally a function of friction, feel and control characteristics, and both methods can be difficult to optimise. One difficulty is to set a compromise trim rate, a value suitable for low airspeeds almost certainly being too high at high airspeeds. In this regard, the type of actuator can have a marked influence. For example, the DC electric motors used in the Lightning trimmers had a significant wind-up time, permitting the application of very small pulsed increments but also providing reasonably fast operation for larger changes. In the TSR-2, AC motors were used which reached full speed almost at once. It was found that the shortest pulse input that could be applied from the stick trim switch was 0·2 seconds, and that this effected a larger than desired trim change in some conditions. For the Panavia Tornado, the DC characteristic was simulated electronically in the motor drive circuitry.

The traditional arrangement of trim switches in a combat aircraft is a combined pitch and roll four way centre off thumb or "coolie hat" switch on the stick top, and a rudder trim switch on the left side console. In the Lockheed SR-71, the rolling moment due to sideslip was so dominant that yaw trimming was a primary function, operated by the stick top trim switch together with the usual pitch trim. The roll trim switch was relegated to the console. The same requirement arose again in the Lockheed F-117A. In transport types, it is more usual to provide only a pitch trim switch on the wheel, with the other trimmers located on the centre stand.

At one time there were a number of accidents caused by trim runaway, typically the result of a "stray positive" in the usual single pole switching, where electrical power was shorted to the actuator or a switch contact welded closed. The risks created by runaway are associated typically with the inability to hold an out of trim stick force with a parallel system if the trim range is wide and the feel gradient high, or with lack of pitch control power with a datum system. An example was the early English Electric Canberra electrically actuated trimming tail, which the pilot could not overpower by the elevator after a runaway in extreme conditions. The problem was overcome by extreme care in trim range adjustment and most importantly by double pole switching. With inherently single pole "coolie hat" switches, a pair could be ganged together, each separately connecting the earth and positive leads. Lifting the gang bar in pre-flight checks allowed each switch to be operated separately to test for dormant faults. This system was very effective though rather clumsy to operate.

Dual motor actuators may be used, the second motor operated by emergency trim switches with a cover guard which cuts off power to the main motor when it is lifted. If the second motor drives in parallel with the main motor through a differential gearbox, a common arrangement, a trim runaway can be halted by selecting the standby trim until the main system is switched off. A second motor running at a slower speed would typically be used also for autopilot trim, and in the Lockheed SR-71 this was also used for the Mach trim in piloted modes.

While relatively simple trimmer installations sufficed for many aircraft, the extreme need for reliability and safety in transport aircraft typically resulted in quite complex arrangements. The example of the Boeing 747 dual hydraulically powered stabiliser trimming system is illustrated in Figure 24. There are three command paths, each of which contains two circuits which must both operate correctly. A pair of mechanical trim selector levers separately arm the hydraulic supply and operate the control valves through a cable system, and these can override any other trim selection. Dual thumb switches (i.e. double pole switching) provide power and selection through electrical circuits, and these can override the autopilot trim system. The hydraulic motors drive through a dual load path differential, so that full torque is available with either both or only one motor operative, at half rate in the latter case. The single jackscrew is supported by a safety rod which holds the screw intact if it should break. To the fullest extent possible, dual paths are provided in signal, mechanical, electrical, hydraulic and structural components.

3.2.5 Structural bending

If the control circuits do not run close to the neutral axis of the wing and fuselage structures, the change of length under normal acceleration bending effectively inserts unwanted control signals in a push rod circuit, or tightens or slackens a cable circuit. In the latter, therefore, the tension is often maintained at a constant value by tension regulators as in Figure 19. (It is noteworthy that while one manufacturer of transport aircraft might use 11 or more regulators in a total control system, another might prefer to use only one, relying on minimising the off-axis location of the cable circuits.) Push rods can be mounted on the alternative sides of lever pivots to reverse their direction of travel at regular intervals, but this is not always practicable.

In the Sepecat Jaguar, push rod compensation for the upper spine bending is applied through electrically sensed deflection measurements to the stability augmentation servos. In the Vought Crusader F8U-1, significant tail input from fuselage deflection under g was measured, giving apparently zero stick fixed manoeuvre margin at high airspeeds (Kraft *et al*). Note that the effect on stick force per g will depend on the feel system type, e.g. q-feel, or spring plus bobweight as in the F8U-1, and on the feel unit location.

3.2.6 Mass balance

While inertia weights have often been added to alter the pitch stick forces, the entire control circuit is also an inertial mass which responds to accelerations by applying forces to the stick. The accelerations are not confined to normal g, but include longitudinal, lateral and rotational accelerations. Often these have undesirable or even unacceptable results, and inertial counterbalance must be applied. Obviously, a cable circuit does not have significant inertial effects, but all control columns, pedals and throttles may do so. Carrier aircraft represent an extreme case of the necessity for longitudinal balance, because of the very high acceleration of the catapult launch.

Push rods are often oriented essentially vertically, acting as a bobweight, where they transfer from the cockpit floor upwards to the spine or upper fuselage region, or downwards back to the tail surface level. They should at least be arranged or otherwise counterbalanced so as not to act as a negative bobweight. Vertical accelerations resulting from pitch acceleration can also introduce unwanted effects, so that different sections of the cir-

cuit which cancel the normal acceleration effect may still require balancing action to cancel unwanted pitching acceleration effects.

Even in transport aircraft, the influence of longitudinal acceleration can be important. Thomas reports on FAR certified aircraft which had to be restrained from pitching when accelerating or decelerating, or when climbing, some of which, when flown hands off, could even be driven progressively into a stall without any self recovery tendency. However, this same effect was apparently responsible for the absence of porpoise tendency on water of the Dornier Do-24 ATT amphibian, the stick pumping automatically in the correct phasing. Longitudinal acceleration of 1 g or more in level or in vertical flight is achievable in some combat aircraft with very high thrust to weight ratio, but even more significant is the axial component of a high normal acceleration when the airframe is at a large angle of attack, all the push rods as well as the stick "falling" to the rear of the aircraft. Three balance weights were used in the Lightning, Figure 25, one on the rudder pedals, one to balance the pitch rods, and one to balance the stick separately which was offset to eliminate normal acceleration coupling on the slightly aft-cranked stick top.

The balance system for a single seat aircraft may need more than a simple adjustment for another stick in a two seat version. Figure 26 sketches the longitudinal control balances of the Alenia AM-X strike aircraft. The single seat system, with a spring and bobweight pitch feel, has no need for aileron circuit balance. In the two seat system, the interconnecting pitch linkage is longitudinally self balanced and the stick mass balance is merely enlarged to allow for the second stick. The unbalanced aileron stick interconnecting linkage requires a new inertia weight installation, but the sticks themselves require no balance.

Sometimes an extreme effect may occur. In the Sepecat Jaguar (Figures 47, 52), the non-linear spring feel cam and pitch gearing, the 1g trim tail angle and longitudinal acceleration acting on the mass of the pitch rods produced the stick force effect shown in curve (a) of Figure 27 in part of the flight envelope. The gradient fell from satisfactory to less than half the specified minimum as the g increased. The addition of inertial balance had markedly different results when it was located either ahead or aft of the mid-fuselage non-linear gearing as shown in curves (b) and (c) respectively. The latter not only reduced the out-of-balance forces but reversed the gradient from one which reduced the stick pull with increasing g to one which increased it. When added to the basic spring feel force, the total result was a steeper and much more linear gradient.

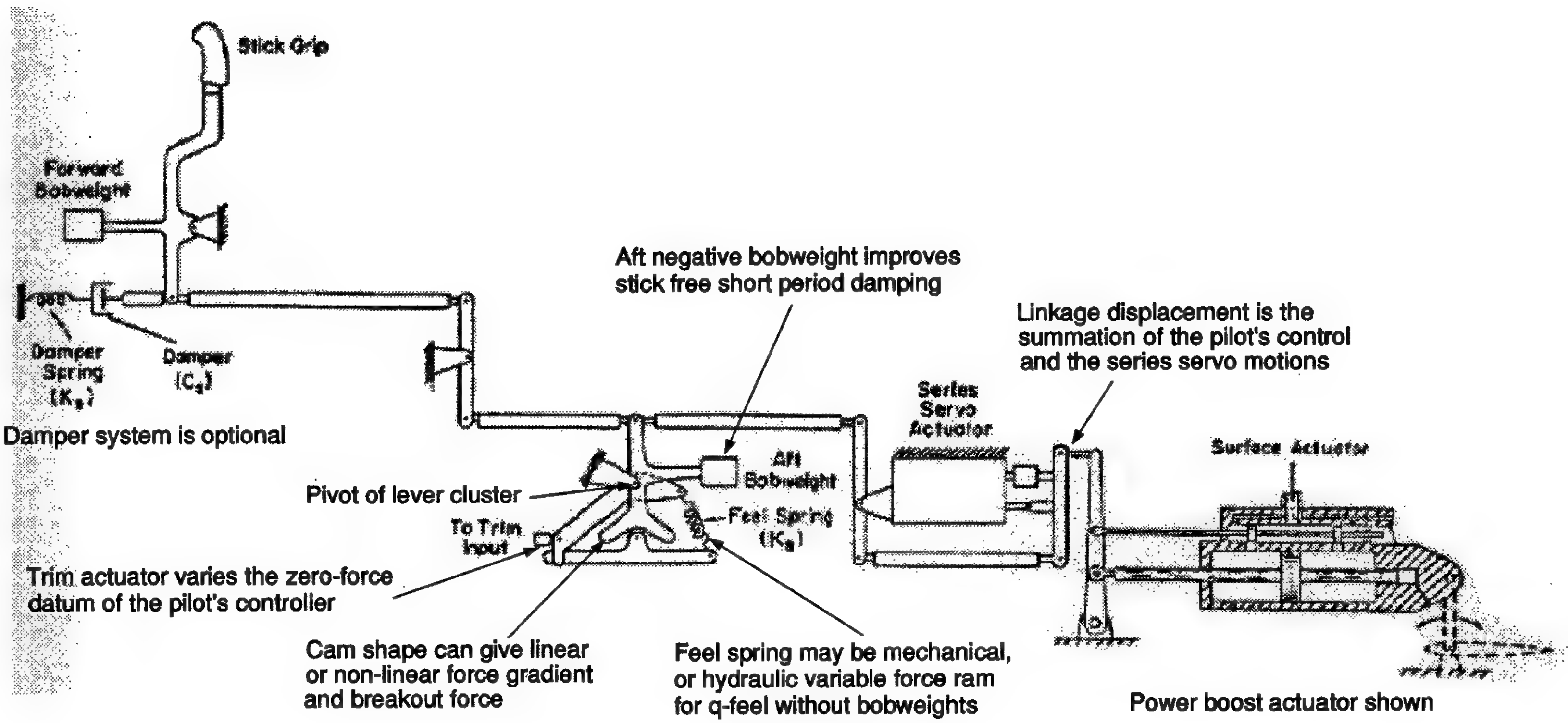
Pitch acceleration coupling is used in double bobweight systems, Figure 14. In the Tornado pitch circuit, well balanced against vertical and longitudinal coupling, pitch acceleration coupling can be detected in flight by reduced stick free damping of the control circuit compared with ground tests, but there is no change in the control circuit natural frequency and no adverse effect on handling. Location of a single bobweight at the aft end of an aircraft is absolutely not to be countenanced, no matter how convenient it may be for design, because of adverse effects on the short period dynamics.

Roll acceleration reaches values several times greater than pitch acceleration. Its most significant effect is the lateral g it exerts on the stick grip and pilot arm mass combination. It effectively acts as a form of negative feedback on sticks which lie above the rolling axis, which is fortunately usually the case, tending to reduce the pilot's input action. In conventional aircraft, this is not known to have caused any handling problem. It is a factor in the roll ratchet phenomenon experienced in a number of fly by wire aircraft, but it is not the primary cause. Ratchet arises from additional phase lags and/or excessive forward path gain in fly by wire systems, where the solution lies. Inertial counterbalancing is difficult because it has to be applied at the same displacement from the rolling axis as the stick grip.

Rigid-body lateral acceleration is not known to have caused control difficulties. Norton reported the example of the lateral structural vibration coupling to the stick of the McDonnell Douglas C-17, an unforeseen result of using a control column rather than a wheel traditionally used in such large aircraft. Many other examples of structurally induced control oscillations in flexible airframes were also given. This suggests that the use of control circuit inertial balancing could be considered for such aircraft to counter this effect.

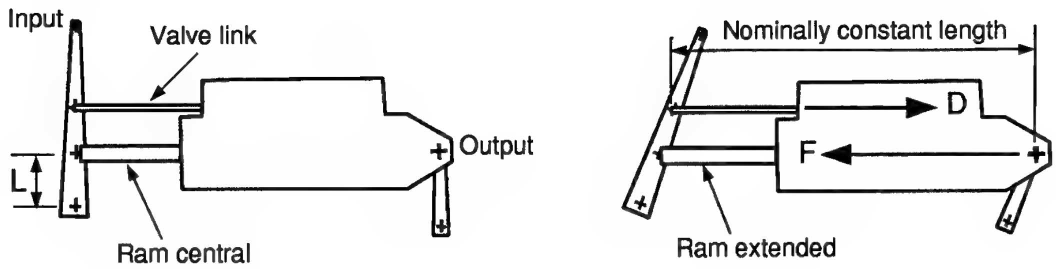
3.2.7 Viscous damping

There is no consistent history in the use of viscous dampers in control circuits. Some aircraft without them have had excellent handling, while others have depended on them to solve control difficulties. Some specific examples of their use are mentioned in the text. They were omitted for example on the Lightning and Tornado because they were considered to be unnecessary. A damper may be fitted merely to smooth out some mechanical imperfection of the circuit, though it should never be considered a substitute for meticulous attention to quality. It is clear that a damper cannot successfully cure severe oscillatory tendencies at high speeds without being excessively over-damped at low speeds. This was a conclusion of the T-38A PIO investigation (Finberg), and is supported by other experience (Dickinson). It is possible to schedule a damper with dynamic pressure, as for example the one in the pitch circuit in the Sepecat Jaguar. Generally, the needs of each design must be considered individually.



Typical of control systems of 1950's and 1960's

Figure 14 Generalised control circuit example

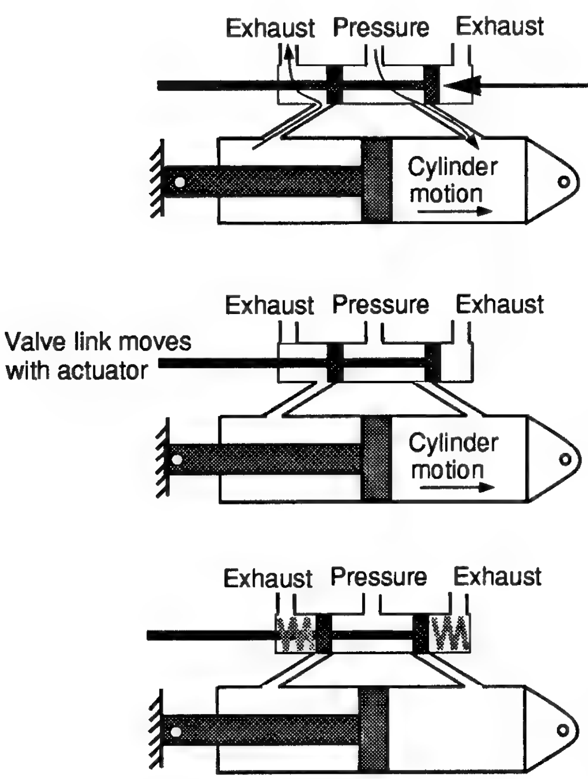


Input/output displacement "D" ratio determined through valve link pathway

Output force "F" fed back through actuator ram pathway

Power boost ratio determined by length "L". Full power control reached when "L" = 0

Figure 15 Principles of power boosted and full power control



Flow-induced force acts to centralise the valve, proportional to flow velocity and actuator rate

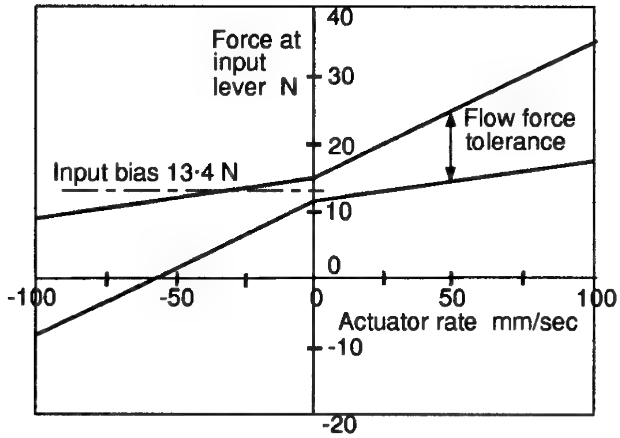
Equivalent to viscous damping in the control circuit

Friction tends to hold the valve open, moving the actuator and pulling the valve linkage and the entire control circuit with it until stopped by pilot or feel force resistance

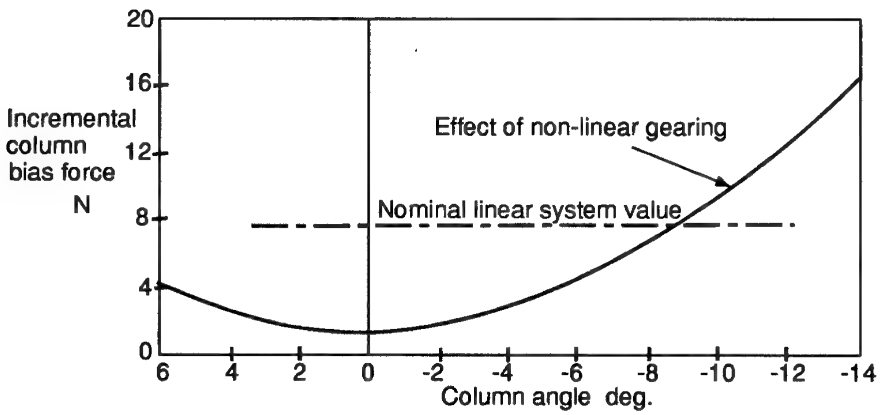
Friction can be countered by valve centralising springs, adding to effect of viscous damping

Use of single valve spring loads out circuit backlash between actuator and feel spring

Figure 16 Power actuation effects on control circuit feel

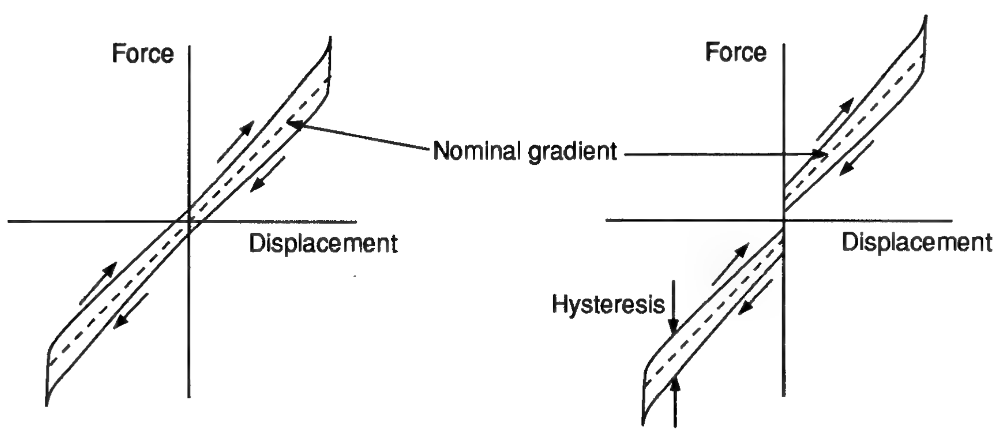


Typical spring biassed valve flow forces



Typical effect of valve bias on column force

Figure 17 Anti-backlash valve bias spring effects



(a) Normal friction curves

(b) Friction with spring breakout

Figure 18 Control circuit friction characteristics

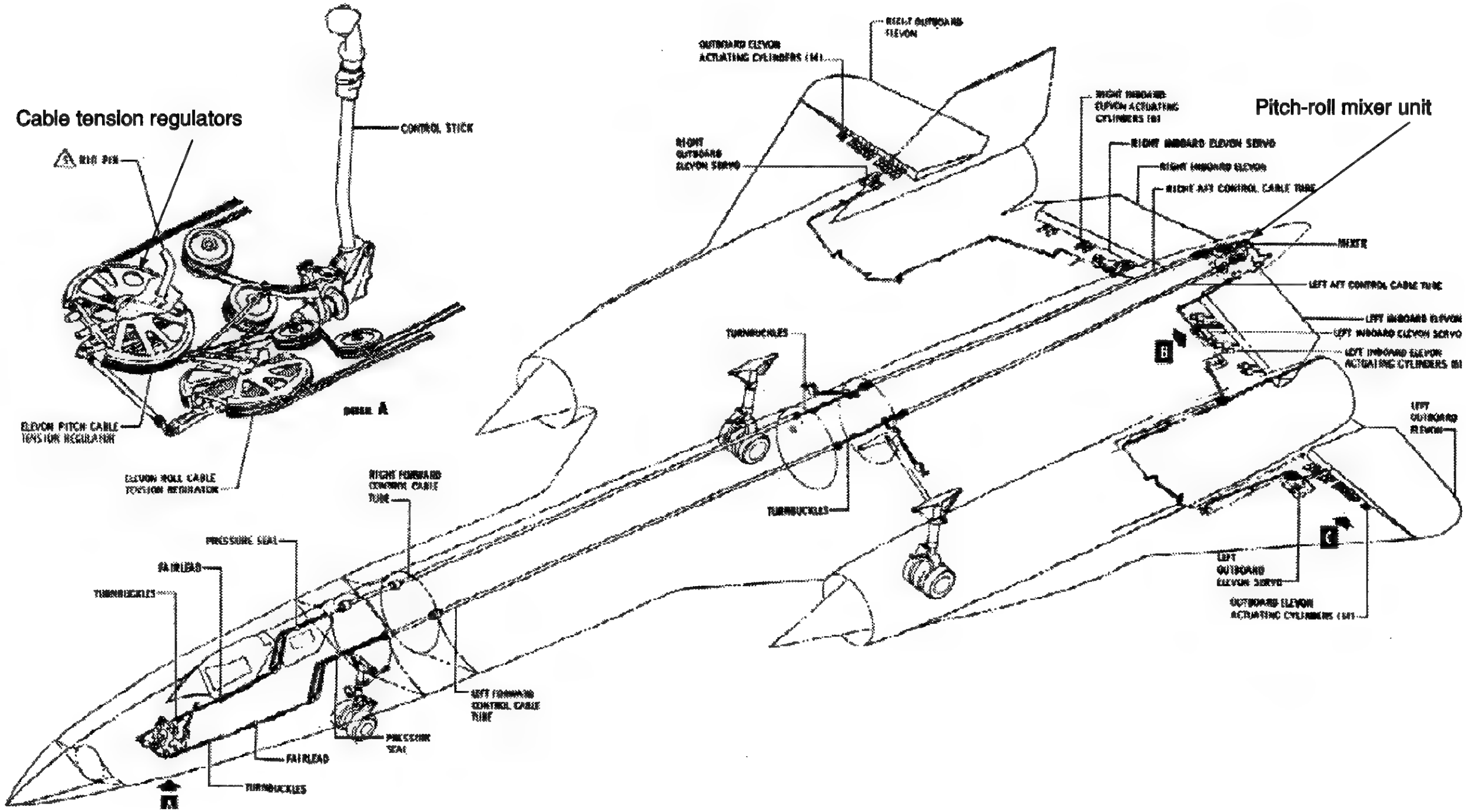


Figure 19 Lockheed SR-71 cable and push rod elevon control system

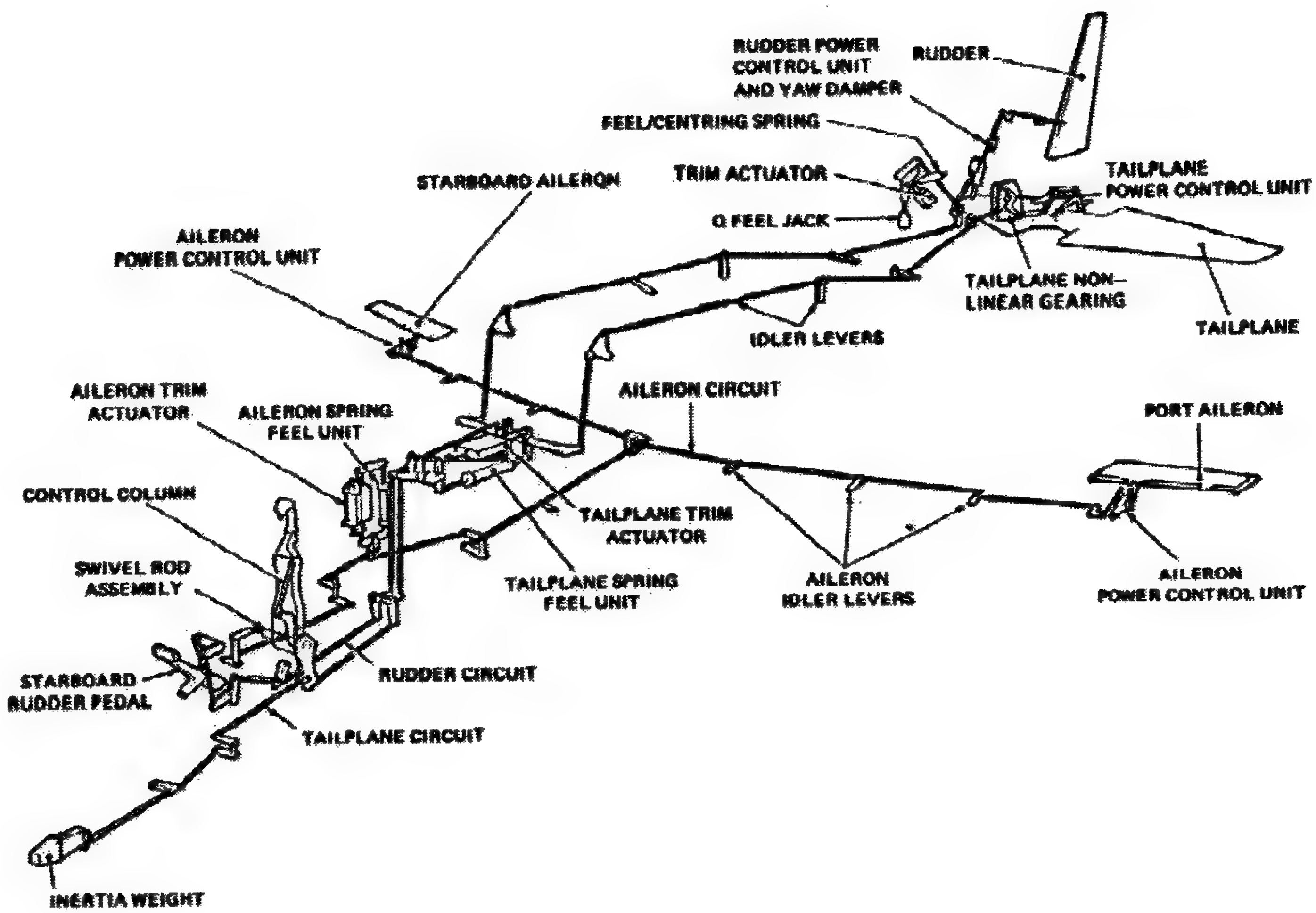
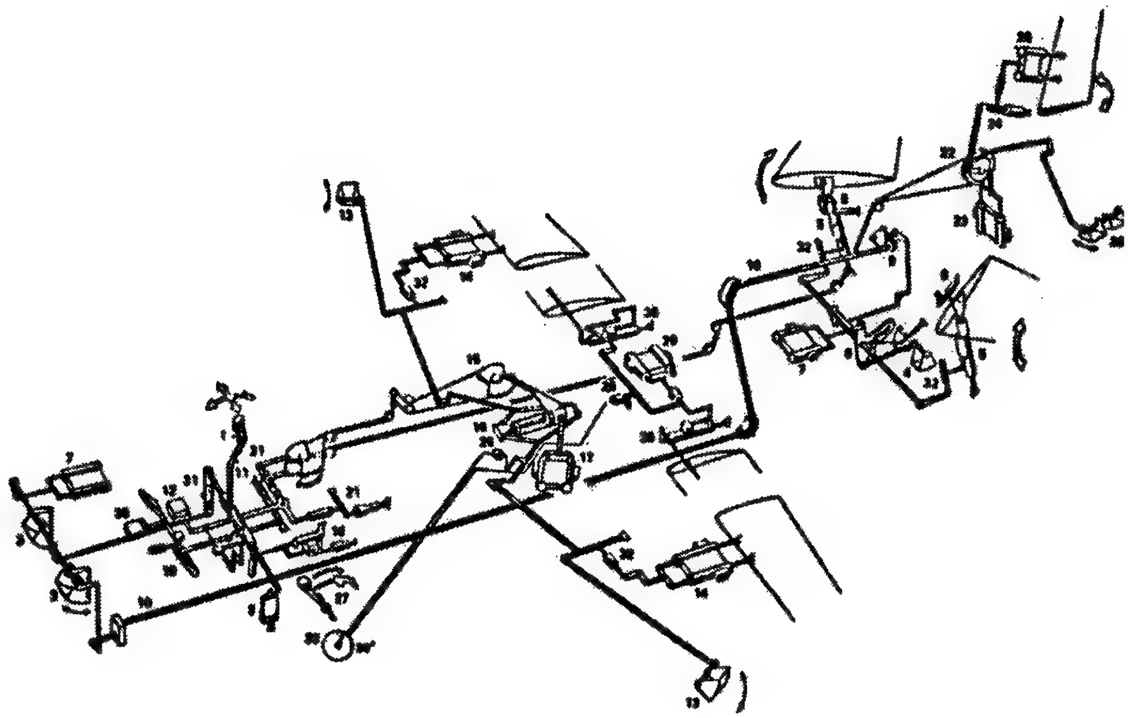


Figure 20 BAe Hawk flight control system



1. COCKPIT CONTROL GRIP
2. POTENTIOMETER (LONGITUDINAL STICK)
3. FORWARD PITCH-CONTROL REACTION NOZZLE
4. REAR PITCH-REACTION NOZZLE
5. TAILPLANE-POWER ACTUATORS (HYDRAULIC)
6. INTERCONNECTING-CAM-LINKAGE OUTPUT
7. DUPLEX ACTUATOR, HYDRAULICALLY OPERATED, ELECTRICALLY SIGNALLED (PITCH AXIS)
8. TAILPLANE DAMPERS
9. REACTION-NOZZLE GEAR AND QUADRANT
10. FORWARD AND REAR NOZZLE INTERCONNECTING TORQUE SHAFT
11. CONTROL COLUMN
12. POTENTIOMETER (LATERAL STICK)
13. ROLL-CONTROL NOZZLE (LEFT AND RIGHT)
14. AILERON-CONTROL DUPLEX ACTUATOR, HYDRAULICALLY OPERATED, ELECTRICALLY SIGNALLED
15. CABLE DRIVE TO TENSIONER UNIT
16. CONTROL INPUTS, MECHANICAL INTEGRATION UNIT
17. DUPLEX SERVO ACTUATOR, ELECTRICALLY SIGNALLED
18. ARTIFICIAL-FEEL UNITS AND TRIM SERVOS
19. RUDDER PEDALS
20. POTENTIOMETER (RUDDER PEDALS)
21. FEEL UNIT
22. CABLE DRIVE TO RUDDER QUADRANT (INPUT)
23. DUPLEX SERVO, HYDRAULICALLY OPERATED, ELECTRICALLY SIGNALLED (YAW AXIS)
24. RUDDER-LIMITER CONTROL
25. DUPLEX RUDDER POWER ACTUATOR
26. YAW-CONTROL REACTION NOZZLES
27. FLAP LEVER
28. TRANSDUCER
29. DUPLEX SERVO ACTUATOR, HYDRAULIC
30. FLAP ACTUATOR (BOTH SIDES), HYDRAULIC
31. HYDRAULIC COUPLING
32. SPRING LINK
33. AILERON- AND FLAP-POSITION INDICATOR

Figure 21 VFW VAK-191B flight control system

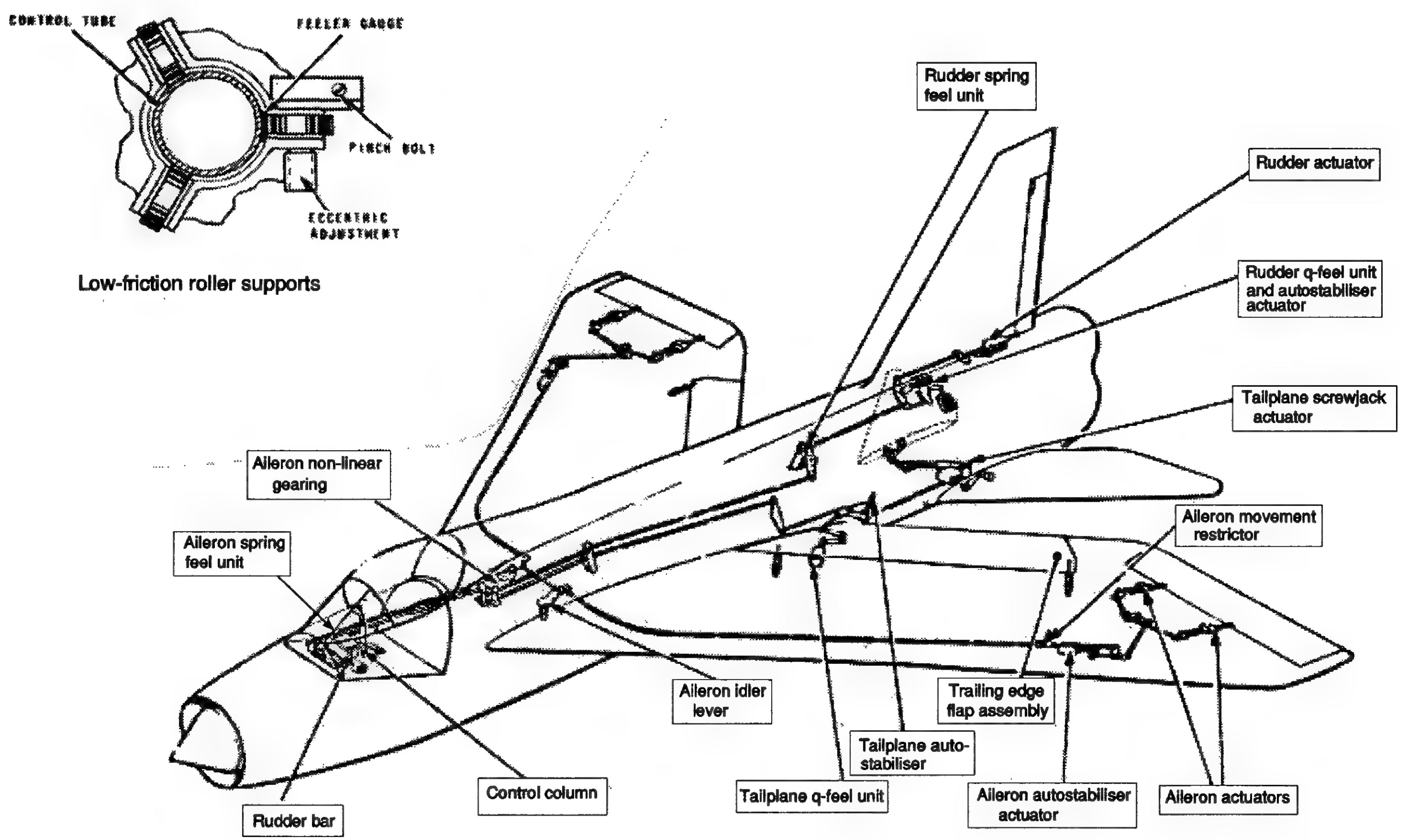
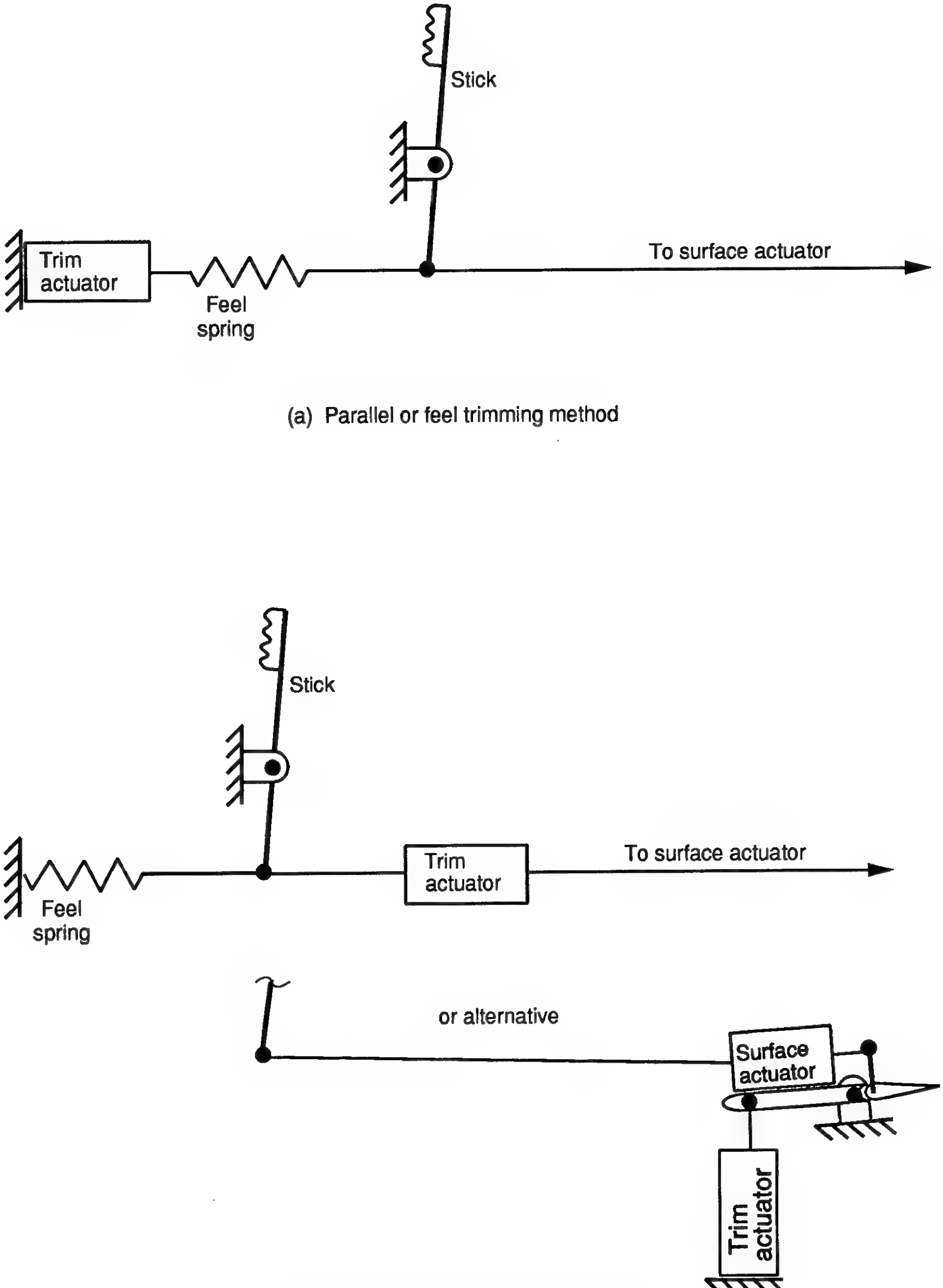


Figure 22 English Electric Lightning flight control system



(a) Parallel or feel trimming method

(b) Series or datum trimming methods

Figure 23 Alternative trim method schematics

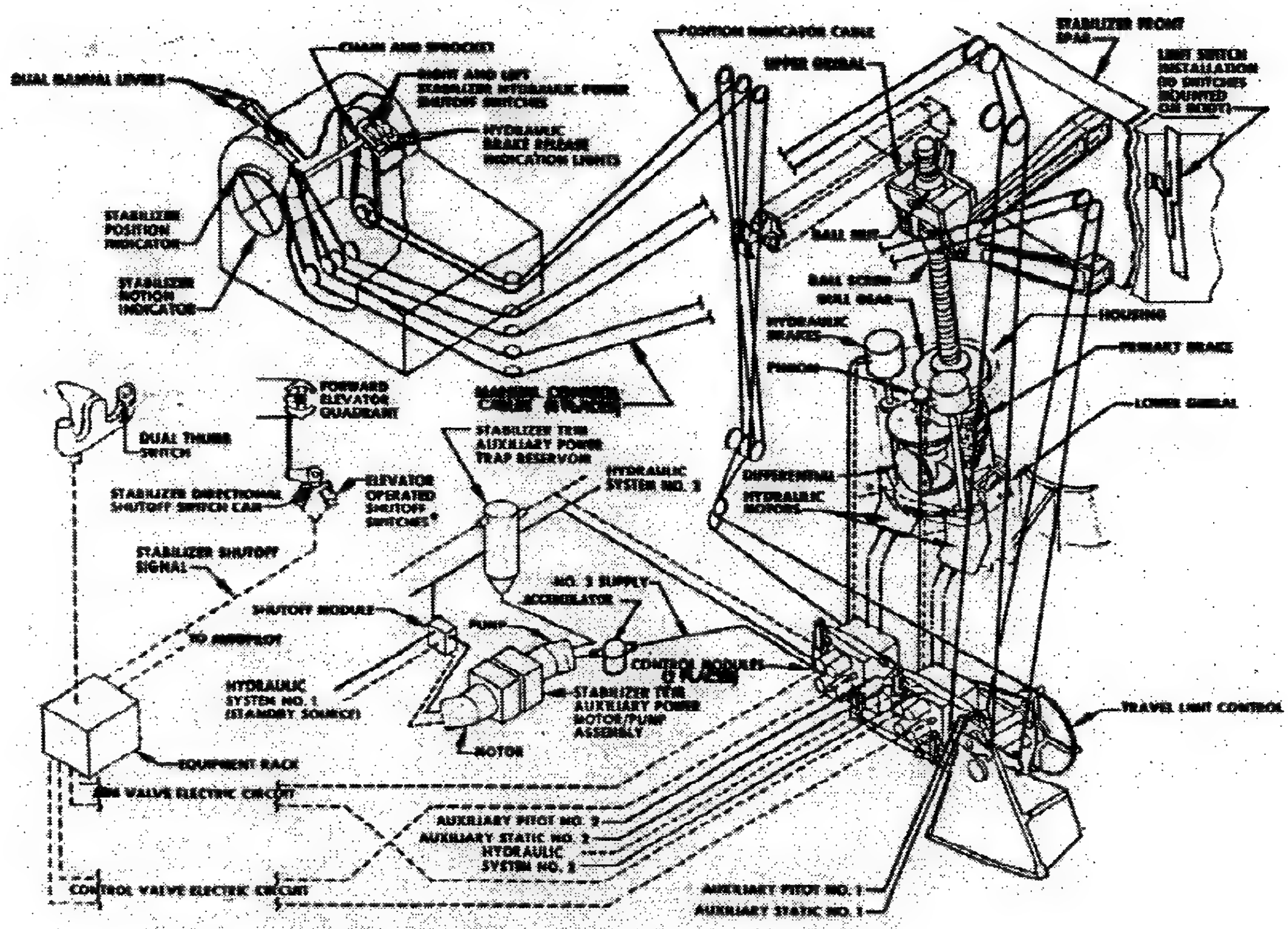


Figure 24 Boeing 747 pitch trim system schematic

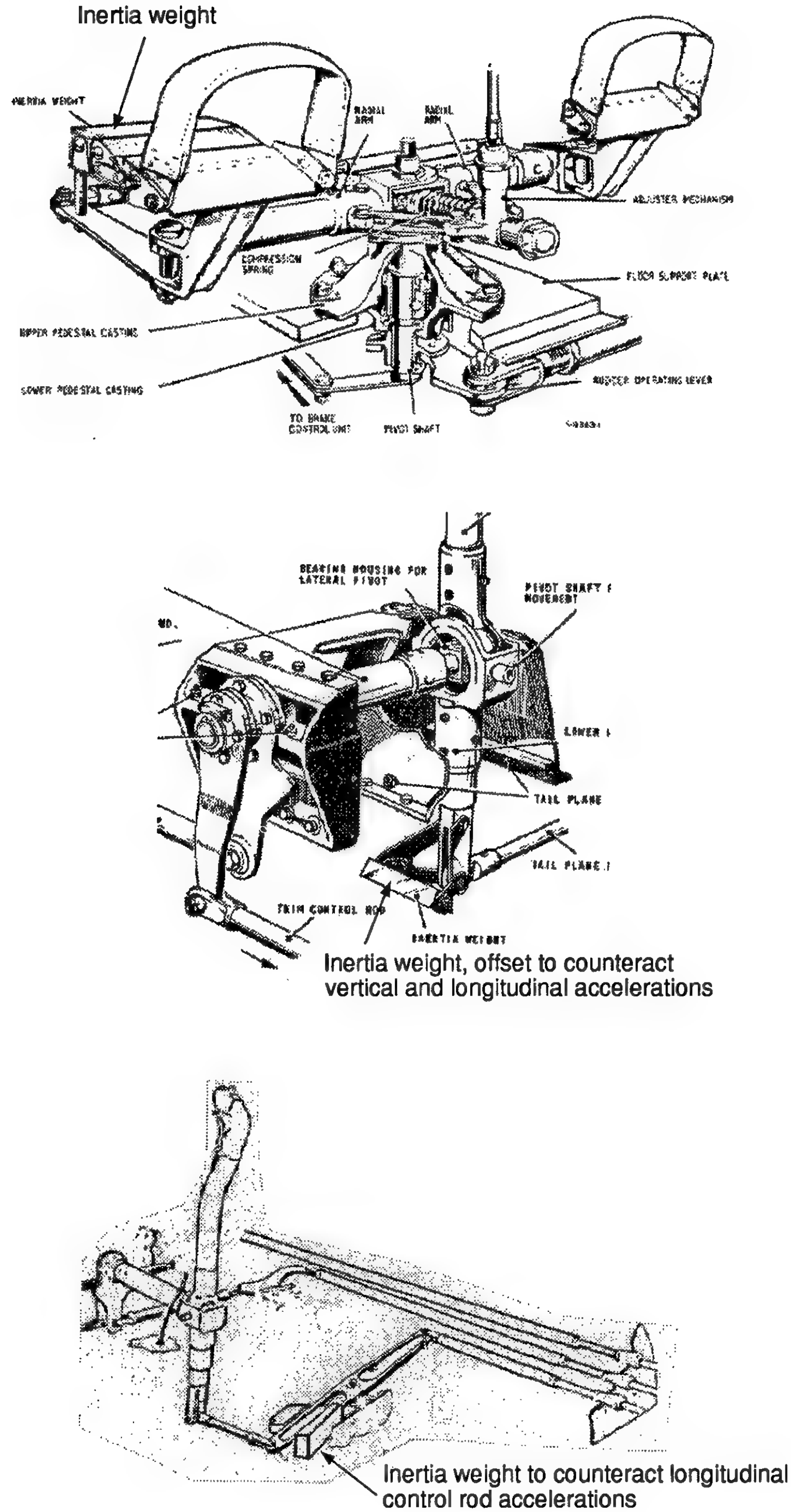
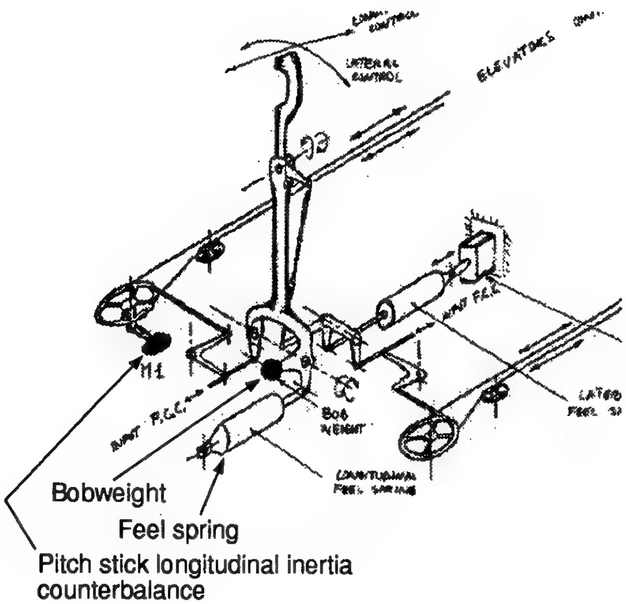
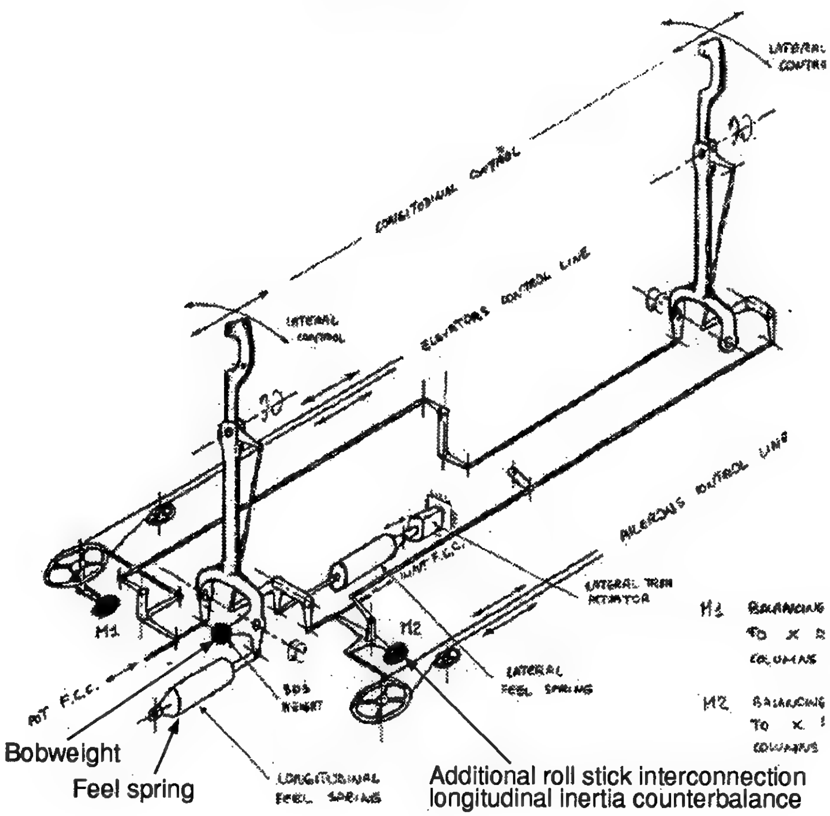


Figure 25 Lightning controls inertial counterbalances

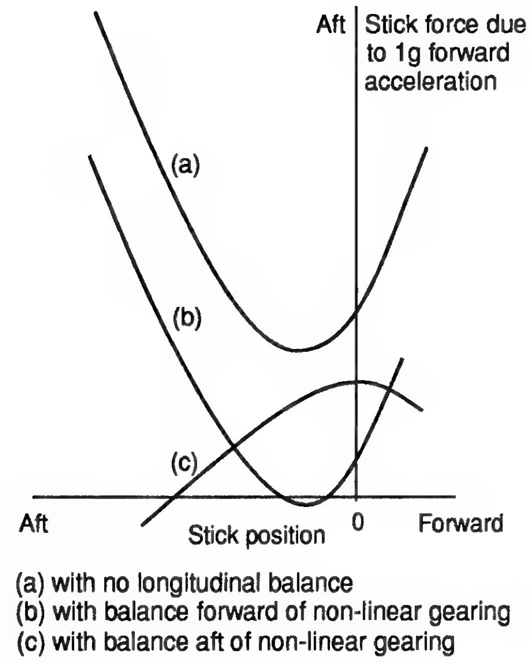


Single seat AM-X

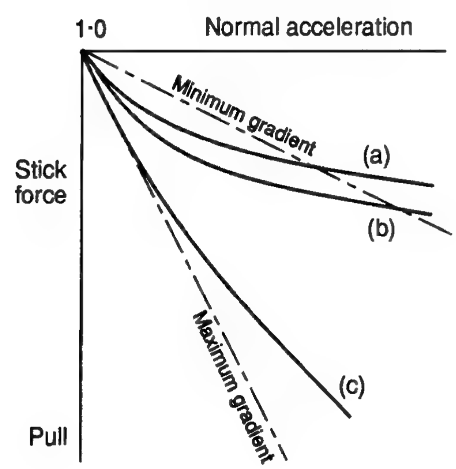


Two seat AM-X

Figure 26 Alenia AM-X controls inertial counterbalance



(a) Stick forces due to longitudinal acceleration



(b) Effects of inertial balance on stick forces

Figure 27 Variations of balance effects combined with non-linear gearing

4.0 ARTIFICIAL FEEL DEVICES

When fully powered control actuation became inevitable, speculation as to the optimum forms of artificial feel force characteristics was based on consideration of characteristics such as those in Figure 28, discussed in Dickinson (1953a). Only the typical shape of the variations with speed is shown, but the relative amplitudes of the curves within each group is significant. Further variations would occur in practice, caused by losses in control effectiveness at high speeds due to compressibility or aeroelastic effects. Additional modifications could be made to the effective characteristics by the use of non-linear gearings, gear change or variable gear ratio devices, and by bobweights which were often referred to as g-restrictors or response feel systems.

Anon (BU AER 1953) discusses the qualities desired for satisfactory feel characteristics and the influence of several artificial feel devices, the spring, pre-loaded spring, q-bellows, ratio changer, bobweights, and stick damper. This early example of pilot/aircraft systems analysis coupled the artificial force producers and the stability augmentation systems into an overall artificial feel concept. This approach does not appear to have been continued, although it is certainly the case that a pilot's opinion of the given dynamic and static behaviour of an aircraft can be markedly influenced by the feel system.

Lang/Dickinson (1961) record the wide variety of feel devices found in some 50 aircraft types or variants. Some general idea of this is given in the following summary:

> In the pitch axis, a considerable number of the example types used spring feel, some with additional devices such as non-linear springs, non-linear gearing, bobweights, and viscous dampers. The control characteristics were on the whole only average or moderately satisfactory at best up into the supersonic region, but many were only marginally acceptable and some were positively dangerous. The several types that used q-feel were all reasonably satisfactory, with no case of oversensitivity or overcontrolling at high airspeeds. This group had the most acceptable longitudinal control and feel, particularly for supersonic fighters.
>
> In the roll axis, almost all used simple spring feel with generally satisfactory results. Early concern that the low speed stick forces would be relatively heavy compared with what pilots were used to, while true, proved to be of no consequence, although a few of the examples were considered to be somewhat sluggish. Only two types, both large subsonic bombers, used q-feel to avoid high speed overstressing, and these had very heavy roll control, so heavy on one that only very low roll rates were possible at high speed. Despite the outstanding success of spring tabs in the Second World War with an essentially V-feel characteristic, there was no support at all for this form with its constant roll rate per unit stick force. Apart from the complication of producing this artificially, roll rates some two or three times greater were now being achieved, and the stick forces would have been too great.
>
> In the yaw axis, simple spring feel was widely used despite the apparent risk of potential overstressing the fin at high speeds. With variable position stops, the result was judged to be fairly satisfactory, the rudder being little used except at take off and low speeds. Q-feel was used to satisfy fin strength stress cases on many types, with very heavy forces at high speeds especially at high Mach number where the rudder effectiveness was reduced. Again, the generally small rudder movements needed at high speed made this completely acceptable.

While some of these opinions were based on aircraft still under development and many of the criticised features were eliminated before issue to the Services, it is worthwhile repeating the summary conclusions because some of these are still main problem areas:

- "Longitudinal control provides the greater problem, lateral and directional rarely cause serious difficulty.
- Minimising of friction and backlash is the most important if not the most difficult issue.
- Devices often attractive on paper such as bobweights, viscous dampers, usually have most adverse side effects and are better avoided.
- The basic problem of necessary stick movements reducing with a power of the speed is becoming great enough to need special treatment. Automatic changes of gearing, or automatic compensation for trim changes, are becoming unavoidable to meet large speed ranges and as such devices are becoming necessary for the avoidance of inertia coupling also, this may represent the future pattern - as indeed might manoeuvre demand systems.
- Non-linear gearings can be useful for lateral control but should be avoided for longitudinal control.
- Trimming systems alleviating force with constant stick position (feel trimming) usually give less development trouble than those involving movement of the stick (datum trimming), though this is probably a matter of degree and of aircraft role.
- The "old" controversy of movement versus force remains unresolved; perhaps the latter is the more important as generally attention to force characteristics evolves an acceptable feel system while in all but limiting cases attention to movement alone would not be adequate.

> Although a definition of the ideal feel system remains as elusive as ever, pilots are able fortunately to operate aircraft satisfactorily with wide variations from their particular ideal; hence a feel system acceptable to all can usually be designed or at worst evolved in development."

It might be thought that the final comment indicates that provision of the best possible feel system is not particularly important, but that would be entirely wrong. It is true that "the best is the enemy of the good", but while the reputation of an aircraft as a "pilots' aeroplane" probably never influenced a sale, such a quality leans heavily on the feel system and is certainly important to pilots in the performance of critical tasks. There is no substitute for a design culture that aims to build in desirable qualities at the beginning rather than grudgingly and expensively to remove unacceptable qualities in development.

4.1 Pitch feel

4.1.1 Spring and bobweight feel

Figure 29 shows the pitch control circuit of the FIAT G91Y. The bobweight is in the form of a heavy control rod in a nearly vertical orientation just aft of the cockpit. It is balanced for 1g by a compensation spring that is installed so that its total change in length is small relative to its own dimensions, and therefore exerts a practically constant force. The spring feel unit attached directly to the stick is of the strut type. If the spring is pre-compressed in its neutral position, a breakout force has to be applied before deflection can occur. Series trimming is used, i.e. the stick trim position is fixed, the trim actuator effectively forming a variable length control rod at the input to the elevator power control. The electrically actuated variable incidence stabiliser follows up the elevator movements, signalled from micro-switches on a linkage driven by the elevator, the whole effectively acting as one unit for increased transonic effectiveness.

This tail arrangement, a considerable improvement over an earlier version with a trimming stabiliser separately signalled from a stick trim switch, was an interim stage towards the ultimate all-moving slab tail. A similar step was made from the North

American F-86A to the F-86E. However, the change from the excessively heavy power boosted high speed aerodynamic feel of the F-86A to the more nearly constant stick force per g of the F-86E with spring and bobweight was accompanied by handling varying from "spongy" at low speeds to "very sensitive indeed" at 400 knots, so much so that the pilot was liable to prolong any short period pitching in his attempts to control it. This of course was the familiar bobweight dynamic problem dealt with in various references, outside the scope of this report, but it emphasises the small part that static stick force per g may play in sensitivity characteristics.

An altogether different spring and bobweight design was employed in the Lockheed F-104, with circuits of the cable type. There is no separate inertia weight, the whole stick assembly itself comprising the 2·9 lb/g bobweight, Figure 30. By means of an ingenious "bootstrap" linkage, forwards and aft movement of the stick causes the stick pivot point to fall and rise about the assembly hinge at the front aileron pulley. The effect of normal accelerations is to pull the stick forwards as with conventional bobweight arrangements. The weight of the assembly is supported at 1g by a pair of long compensation springs. Another effect is that as the stick moves rearwards, the grip follows a more horizontal path instead of dropping down. This was designed to ensure clearance from the seat and ejection "D" ring, but it also alleviates a common source of difficulty of applying large lateral control displacements with the stick held aft. Figure 31 shows the great complexity typical of many mechanical flight control systems, confined within an extremely small packaging space. Fortunately the roller and cam spring feel device is extremely compact. Datum trimming is used, the trim actuator forming a variable length final input link to the power actuator.

The BAe Hawk bobweight system, already shown in Figure 20, is straightforward. The feel spring is of the strut type, with parallel feel trimming, and the bobweight illustrates the usual separate inertia weight. In this case it is attached to an extension linkage at a position as far forward as possible, picking up the maximum pitch acceleration in accordance with standard solutions to improving the dynamic behaviour of such a system.

A spring strut feel unit is readily adjustable, either by replacing the springs or adjusting the pre-load, and is capable of providing both a spring breakout and one or more gradients of reducing stiffness with increasing deflection. It requires a very high standard of design and manufacture if unsatisfactory friction and hysteresis is to be avoided. The roller and cam device of Figure 14 is inherently free-running in operation but also requires considerable design and manufacturing precision to avoid either slackness or an irritating "click" in the central position. It can provide any smooth non-linearity desired but can only be altered by machining a new cam.

4.1.2 Q-feel

The principle of a q-feel device is sketched in Figure 32. The piston exerts a force which tends to keep the stick centralised. The force acts at an arm length effectively proportional to the deflection of the stick, providing a linear spring force gradient at the stick. The feel force is proportional to dynamic pressure measured in the pitot-static system, and therefore reflects the indicated or calibrated airspeed rather than an exact equivalent airspeed particularly at supersonic speeds. This is not significant because the longitudinal control power is then no longer proportional to dynamic pressure in any case.

In the simple q-bellows or q-pot of the type described in BU AER (1953), the pitot and static pressures are connected directly to opposite sides of a bellows type piston, which has to be relatively large to generate the required forces. Hydraulic q-feel, as developed by H M Hobson Ltd in the U.K., was widely used from the 1950's, and by the 1960's was in use in at least 15 military and civil aircraft types from the smallest, the Folland Gnat light fighter, to the largest, the Lockheed C-5A, and in the fastest, the 800 knots at sea level BAC TSR-2. A small piston is supplied with a variable hydraulic pressure proportional to q, derived from a feel simulator with the basic features shown in Figure 32. This is simply a pressure regulator valve, amplifying the pitot/static force (P-s) by the ratio of the diaphragm to valve areas. As (P-s) increases, the valve opens the inlet port until the controlled signal pressure acting on the end of the valve restores force balance with the diaphragm. Similarly, signal pressure is bled off through the exhaust port as (P-s) decreases.

A complete q-feel simulator and jack system is illustrated in Figure 34, with a number of additional detail features necessary for satisfactory operation. These include valve and diaphragm springs, a fail-safe relief valve and a damper. Figure 35 shows the basic pressure adjustments that are possible. The minimum "base" pressure is controlled by the valve spring, and the break point at which the pressure starts to increase is controlled by the diaphragm spring. The relief valve prevents excessive stick forces if the control valve seizes with the inlet open, providing 30% greater forces than normal, but feel is lost if the valve seizes with the exhaust open. The additional range of EAS, altitude, single Mach and double Mach corrections, together with further mechanical input and non-linear gradient adjustments, can be obtained by the schematic modifications to the simulator design in Figure 36. The result is an extremely powerful and flexible tool for the enhancement of flying qualities through stick force variations.

The English Electric Lightning (1954), designed strictly to a high altitude supersonic interceptor requirement, used the single Mach correction to cater for its extremely wide flight envelope. Figure 37 (a) to (c) show a generalised picture of its tail trim, tail angle per g and the resulting stick forces. The supersonic forces are substantially higher than the subsonic, but their spread at a given Mach number is quite small. Although a double Mach correction simulator was tested to reduce this variation, it was found not to be necessary. In its supersonic high altitude primary envelope, the full tail angle could be applied without exceeding the strength limit and without excessive pilot effort, because of the reduction in available tail angle with altitude due to the trim changes and to the reduced feel gradient due to the Mach correction (Fig. 35e).

When its operational envelope was later extended to include low altitude high speed conditions, its aft centre of gravity limit was set by the low stick forces, a value of 2 lb/g being determined as the minimum acceptable for service pilots. This resulted simply from lightness of control, and not from any dynamic misbehaviour. With a manoeuvre margin of only some 2 or 3%, the short period response was highly damped even without autostabilisation, and the inertially uncoupled control circuit had no effect on the stick free dynamics. The result was its notably precise and steady control response. However, a trial was made of a 2 lb/g bobweight installation in an attempt to extend the centre of gravity range. An initial version with a single bobweight resulted in a neutral damping of the free stick at high airspeeds, though this was not dangerously coupled with the short period oscillation. This was readily cured by the addition of a viscous damper, and a double bobweight was also tried. With no real improvement, it was not adopted.

Despite the nominal subsonic q-feel, it will be seen that the stick force per g increases at low EAS. This was caused, not by adjustment of the simulator pressure, but by the added gradient of the mechanical emergency spring feel device on the unduplicated feel jack, Figure 38. This feel jack, in line with the intensive reduction of friction practised on that aircraft, was reversed so that the piston rod gland was subjected only to exhaust pressure, the signal pressure acting on the far side of the piston acting to push it outwards. Deflection of the operating lever pulled the roller-guided cross head inwards against the piston. Although the prototype feel jacks were fitted with spring-cam centring, this was deleted, sufficient centring being achieved due to the low friction with no additional breakout force.

The very satisfactory Lightning feel in the subsonic regime led to a proposal to modify the nominal specification stick force per

g boundary (Gibson 1978) as shown in Figure 37(d). This suggested constant limit values at high EAS, i.e. q-feel, constant force per unit pitch rate slopes at intermediate EAS in accordance with Northrop practice at the time, i.e. V-feel, and constant force per unit angle of attack at low EAS. Although in principle conventional aircraft maintain essentially constant stick force per g in low to moderate Mach number flight, it was frequently found that forces suitable for the landing approach, where only small manoeuvres could be generated, were around 8 to 20 lbs/g. These are much too high for a high g aircraft in operational conditions. This desirable speed variation can be produced either by feel simulator pressure adjustments, or by an additional mechanical spring feel. (It occurs to an extent with a spring and bobweight system where the spring contributes an increasing stick force per g with increasing tail angle per g).

The principle of "pseudo-V-feel" was used also in the Blackburn Buccaneer, Figure 39. Its original pitch feel system comprised a fixed datum stick with a non-linear ±7° tail authority, a series trimmer to provide the remainder of the total 28° tail angle, and only a fixed spring feel with a maximum stick force of 16·5 lbs. Detailed development reduced the friction breakout from 4 lbs to 0·5 lbs, an essential feature for its high speed very low altitude role. A major development of the feel system was required, with the addition of a q-feel unit providing a maximum stick force of 62 lbs at high speed, reduction of the spring feel to 9 lbs maximum, and increase of stick authority to ±9·5°.

The importance of apparently minor details is emphasised by a fatal test take-off with mis-trim of a prototype, during which the aircraft pitched up. Despite the recorded application of a very high forward stick force, it did not recover. A viscous damper was fitted between the non-linear gearing and the tailplane control actuator. The effective damping at the stick is a function of the square of the gearing ratio to the damper. As this ratio varied by 4:1 between stick neutral and full deflection, the damper effectiveness increased by 16:1, and the pilot was prevented from moving the stick forward quickly enough. The damper was afterwards moved forward of the non-linear gearing.

The Buccaneer was also prone to pitch-up departure caused by snatch pulls in extreme operational conditions at very low level (Dennis). The usual stick force requirements typically require that the pull to reach the normal acceleration limit should not exceed 56 lbs or thereabouts. This is only moderately heavy and does not protect an aircraft from much higher forces applied transiently in an emergency avoidance manoeuvre. Pilots can readily pull 70 lbs or more in such a situation, and ground tests have showed that a single-handed pull of 90 to 110 lbs is possible for some pilots. An attempt was made to prevent the pitch-up by fitment of a modified damper designed to operate only at specific stick positions and in the aft direction, as seen in Figure 39 for two versions. The non-linear characteristics are shown for a constant rearward stick rate of 6 inches per second, judged to signify the onset of a snatch pull incident. The damper force is negligible for all forward movement of the stick in any position and for aft movement while the stick is forward of the point shown. The intention was to warn the pilot by the sudden increase in forces to reverse the stick input movement.

The higher force unit was not acceptable because it grossly interfered with many normal manoeuvring operations, requiring two-handed control and causing excessive fatigue after only a few minutes. The second damper was more successful, and actually improved certain manoeuvres such as rotation for take off and the pull up for toss bombing. However, closer attention to and anticipation of trimming in the approach and landing was necessary. Due to the datum trimming and fixed stick neutral position, failure to maintain close trim led to excessive forces as the stick was moved aft with reducing speed. Although it showed promise, the damper was not adopted finally because it still could not guarantee protection from extreme cases.

The exceptionally wide range of aerodynamic geometry and flight envelope of the variable wing sweep fly by wire Panavia Tornado, together with pitch/roll mechanical reversion, necessitated a duplicated Mach-compensated q-feel simulator schedule in Figure 40, modified by mechanical input from the wing sweep actuator unit as in Figure 36e. The base level is largely provided by a springbox feel strut which acts also as a last resort feel source. The q-dependent gradients are reduced as the sweep increases. A moderate breakout force, not shown here, is derived from the internal settings of the springbox. This provides good centring, but at the same time it is possible to initiate stick movement with relatively light finger pressure, there being no tendency to "click into a groove".

The earliest q-feel system on an airliner was that of the Boeing 727, Figure 41. The feel unit is mounted on the stabiliser along with the aft control cable quadrants. A dual hydraulic feel system is achieved by two independent simulators signalling two pistons, one of them free floating, contained in the feel jack cylinder. The output force applied to the q-feel roller/cam is that of the piston subjected to the higher simulator signal pressure. A spring breakout roller/cam device is used to provide positive centring and a small fixed contribution to the feel forces. Trimming is performed by electric actuation of the stabiliser, and is therefore of the datum shift type. If one hydraulic supply fails, there is no significant change in feel. If both hydraulic supplies fail, a mechanical reversion spring is released to exert a constant force on the q-feel roller. In this condition, pitch control is effected through elevator servo tabs and the electric stabiliser trim. Feel is then provided both by the tabs and by the spring reversion feel. The feel system performs the additional function of limiting the effects of an autopilot hardover. The pitch control, clutched to and moving with the elevator actuators, is loaded by the feel unit until the clutch is overridden and disengages the autopilot actuator.

Further pitch feel refinements followed in the later Boeing aircraft. Figure 42 is a schematic of the Boeing 747 duplicated feel unit. The q-feel force is applied by direct tension on the output crank as in Figure 32, but the tie rod is split into twin slotted straps. As deflections increase, the leading strap tension increases while the trailing strap tension decreases. When the leading strap is aligned with the tie bar at 5° elevator angle, the trailing strap is loosened as the pins become free in the slots. The result is a steep feel gradient within this range for excellent centring and a greatly reduced gradient beyond it to prevent excessively large maximum forces as shown in the sketch. A secondary spring roller/cam centring and minimum feel device is also provided, there being no other auxiliary feel device to cater for double feel failure.

A feature to be noted is that the relationship between the stick position and elevator deflection varies substantially with changes in speed, despite the absence of an explicit variable gearing. This results from the increasing stretch in the control cable and pulley mounting system as the feel force gradients increase. There is an obvious influence on the control sensitivity, but it also alleviates the very high stick force to deflection stiffness gradient that would otherwise occur at the maximum speed.

The diagrams in Figures 41 and 42 show a feature used on a number of transport aircraft to reduce the wide spread of stick forces arising from the large centre of gravity range. The pitot-static diaphragm in the feel simulator applies force to the feel pressure balance valve through a spring. An additional spring is positioned by a cam driven from the stabiliser position, altering the proportion of pitot-static force reaching the valve. Most of the adjustment of the feel pressure takes place within a small range of stabiliser positions, resulting in a wide variation appropriate to the effects of C.G. shift in cruising conditions, Figure 43. This modified feel pressure is used to control the pitch trim rates as shown, being more closely related to the CG-modified control power than the nominal dynamic pressure would be. In the earlier Boeing 727 a low or high speed trim rate was selected by the pilot. Another example with stabiliser-related feel gradient modification is the Lockheed C-5A q-feel system, with an input of the type in Figure 36e.

Figure 44 shows the Boeing 767 stick nudger (required only by one airline) attached to the pitch feel unit, activated when the angle of attack reaches 12°. This alters the line of action of a spring across the output crank pivot, applying a nose down force to the stick increasing to about 25 lbs over 5·5 seconds. It is deactivated when the angle of attack returns below 11°.

Another variant of the duplicated plus emergency feel device was used on the BAC 111 airliner, Figure 45. Two totally separate integrated altitude-corrected simulator and feel jack units pull a whiffletree lever connected by links and a roller/cam to the input lever. This arrangement ensures there is no significant change of feel when one unit fails. An additional supplementary jack is pressurised from a third hydraulic supply after failure of the two feel unit supplies, applying a constant force equivalent to normal feel at an airspeed of 150 knots.

4.1.3 Variable spring feel

Variable rate forms of mechanical spring feel have been successfully used. One example is the Lucas feel unit in the Canadair CL 600, Figure 46, a pair of springs operating side by side for duplication. This has a two-slope characteristic derived from twin springs in series, one with a variable rate controlled by the stabiliser position.

The Sepecat Jaguar pitch feel is dominated by a non-linear gearing (§4.1.4), with feel forces provided by a variable force gradient spring roller/cam device, known as the "Ajax", shown schematically in Figure 47. This is scheduled with dynamic pressure, although it does not qualify as a q-feel system because the stiffness range was reduced considerably during flight testing with development of the non-linear gearing. The centre notch feel characteristic, probably common to many roller/cam devices, caused some development problems for the primary high speed low altitude operational role, but eventually a satisfactory compromise was attained.

The Boeing 777 system is fly by wire with no control circuits to the rear of the airframe. It is included here because it represents the classical feel of a normal pitch system with the devices shown in Figure 48. Each column drives its own independent mechanical spring variable feel unit adjusted by a speed scheduled screwjack actuator, providing half the total feel. A compliance spring between each stick and its feel unit introduces additional stick deflection with a stiffness of nearly 50 lbs. per degree of column movement. This is similar to the customary cable stretch which causes substantial variations in stick stiffness on other large aircraft with the feel units located at the rear (noted in §4.1.2). The column fore and aft inertia balance weights have been mentioned in an earlier paragraph, and the feel qualities are further enhanced by viscous dampers. Trim operation differs from past types, giving direct control of the stabiliser position only for the take off setting. In flight the trim switches change the reference airspeed in the manoeuvre demand control laws, which control the stabiliser setting directly. The example of a force-displacement test result shows an entirely conventional characteristic, which was a primary design aim to prevent the unnatural feel thought to arise with many fly by wire sticks. It shows positive centring with relatively small additional friction typical of good quality systems.

4.1.4 Non-linear gearing

The intention of using a pitch non-linear gearing is primarily to reduce control oversensitivity at high speed flight conditions by increasing the stick movements relative to a linear system. Asadourian, reporting on simulation of such a gearing, noted that pilots could perform tracking "almost as well" as with linear control, but it was unanimously held to be undesirable because of lack of response through the neutral range. The result was increased lag, higher stick forces and greater pilot concentration during tracking. Situations requiring rapid control motions in low-damped aircraft could easily result in overshoots exceeding the design limits. Lang/Dickinson also criticised markedly non-linear gearings in association with series trimming. This meant that the stick was normally operating at the neutral position at all flight conditions, leading sometimes to very large displacements and forces. If trimming was not performed and the stick was held off-centre, however, the force gradients could become dangerously light. Change of trim with store release, Mach number, or configuration could move the stick to a high gearing with risk of overcontrolling.

However, a notable and probably unique example of such a gearing with only a fixed spring feel and series trimming is found in the Lockheed SR-71. Despite its astonishing performance, it could use a simple feel system because of its essentially non-manoeuvring cruise role without external store carriage. Although it used triple redundant stability augmentation to alleviate the effects of the low stability margins necessitated by performance requirements and of low damping at very high altitudes, it remained controllable with the augmentation inoperative.

Figure 49 shows the SR-71 pitch-roll mixer unit at the rear of the fuselage, driving two servo units in each wing controlling a total of forty "elevon" surface actuating cylinders. The mixer contains pitch and roll feel springs, pitch and roll twin motor manual/autopilot/Mach trim actuators, a pitch non-linear gearing, pitch input stops, a stick pusher, and an anti-bias spring to balance the valve bias springs in the elevon servo units (refer to § 3.1.2). It is an outstanding example of the mechanical control designer's art, shown here in some detail to enable its workings to be appreciated. The stick displacement and force to elevon ratio varies by some ten to one between neutral and full up elevon. Because of the series trimming the initial stick position is the same for all trim states, and the non-linearity alleviates the otherwise excessive forces for large deflections. This is acceptable for its limited cruise role.

Non-linear gearings with parallel trimming have also been used successfully. It is difficult to avoid some non-linearity in any case. Any pair of control levers joined by a rod forms a four bar chain, producing a non-linear input-output relationship unless set up exactly as intended. Any control system with a collection of levers joined by rods is therefore potentially non-linear, a fact made use of for example in the English Electric Lightning development flying as the tailplane travel limits changed. The pilots insisted that the stick to tail gearing was not to be reduced at trim conditions for high speed subsonic flight, which was satisfied by variations in the gearing curvature at large negative tail settings where the control sensitivity was inherently low.

A simple non-linear gearing was integrated directly into the stick output to the pitch circuit of the BAC TSR-2, Figure 50. An essentially linear stick force to surface deflection relationship is obtained by another non-linear gearing between the stick and duplex feel unit, with slopes approximately the square root of the primary gear slopes. This aircraft was designed for very high speed operation "on the deck". Concern about pitch control sensitivity and accuracy dominated the design of the large actuators of unprecedented precision, the valve flow forces, and circuit backlash, stretch and damping. The gearing substantially increased the stick displacements per g at forward stick positions, where the beneficial reduction of circuit inertia was fortuitous and welcome. The corresponding increase in inertia at low speed trim fortunately was acceptable with the addition of a circuit damper. The duplex full authority terrain following autopilot, which clutched the circuits to the main tail actuators, had the safety features of more-nose-up-of-two selection, response monitors, clutch disengage against excessive feel forces, and the pilot over-ride cut-out. The arrangement of the latter allowed the pilot to revert to manual control by grasping the stick at a switching force level independent of the clutch disengage setting.

This principle was incorporated into the Tornado mechanical reversion control circuit by a specific non-linear lever pairing as shown in Figure 51. The characteristic stick gearing typical of these designs is sketched in the figure. Although there is a five

to one variation in the gearing slope from end to end, this occurs gradually over the total travel. The fly by wire stick position pick-offs are driven by a similar non-linear gearing. Compared with a linear system, the practical variation is not extreme, with no more than about a 50% increase in stick movement at typical high speed trim, and at low speeds the travel is not less than about 75%. Trim variations at a given flight condition can be quite substantial without gross effects on the gearing ratio. With a compensating non-linear q-feel unit gearing as noted above, the resulting stick force per degree of control demand varies by only 5% over a range of tail angles on either side of a nominal high speed datum. The only development required was some reduction in overall gradients, with a further 30% reduction for the U.K. ADV air defence variant with its changed role.

A different type of non-linear gearing is illustrated in Figure 52, a schematic of the Jaguar device. The severity of the gearing curve is controlled by the eccentricity of the output rod pick-up point on the small gear wheel, i.e. its radius relative to the gear pitch circle diameter. This ranges from linear at zero eccentricity to a curve similar to the sketch for an eccentricity of about 0·8. The variation in gearing slope is more than ten to one, and a very large part of this occurs over a small range of tail angles. Because of the parallel trimming, the initial stick position varies with the trim state. The change in slope for relatively small trim changes is very considerable, and selection of the tail angle for the point of inflection with the maximum slope is extremely critical. Additional development problems mentioned earlier include the longitudinal control circuit inertial balance and the trim change with afterburning selection at transonic speeds. For an aircraft that carries and drops a wide variety of underwing stores, optimisation of such a gearing can be very prolonged, though in this case it was ultimately very successful. In service use, maintenance of the correct rigging of the system assumes extreme importance. For aircraft such as the BAe Hawk trainer with a similar gearing, the absence of external stores simplifies the development considerably.

Such extreme non-linear gearings can also introduce unusual effects. For example, the lightest stick forces for the Jaguar occurred in a highly stable condition, and the heaviest forces in a low stability condition, resulting from the different trim points. Negative g stick forces may be rather large as the stick has to traverse through the inflection point, and they may be rather non-linear. Whether or not the gearing reduces or increases the usual larger supersonic stick forces depends on which way the trim curve moves, and they are likely to be substantially non-linear in either direction. Although some linearising compensation is possible in the shaping of a roller/cam such as in the Ajax unit, this can never be complete because of the wide range of force/displacement variations.

All non-linear gearings have the desirable effect of bringing the stick nearer to the pilot at high subsonic speeds, where the tail angle is typically not far from its positive limit. They can also bring the stick uncomfortably close to the pilot at low speeds with high lift flaps extended if the trim change with flaps is nose down, in turn making lateral control more awkward. It is possible in extreme cases for the apparent approach speed stability, reflected in the stick trim position with speed, to reduce as the CG moves forward and the stick trim position moves further aft. To alleviate both effects, advantage can be taken of a large flap trim change by automatic series trim compensation in which the stick position remains fixed, and hence remains substantially further forward from the pilot.

4.1.5 Variable gearing

Although seldom used in more recent times, a number of early powered control aircraft used gear change devices, usually with a simple linear spring feel. Typically the change in gearing ranged from 1·5:1 up to 3:1, and was effected simply on gear or flap retraction, and possibly also by a Mach switch, or automatically with varying flight condition. These devices changed the ratio slowly enough to be barely noticeable, and gave effectively linear control at given conditions. However, failure cases need to be given careful consideration. A datum trim runaway could apply more control than can be overridden by the stick, or a gearing failure could leave insufficient control for landing. It is also necessary to position the feel and gearing components carefully, ensuring that a gear change does not apply undemanded control inputs. This must be considered not only for level flight but also for hard manoeuvres, since the aircraft is very likely to change speed very quickly while the stick is pulled back, with the potential for a rapid pitch-up as the gearing changes.

The Dassault/Dornier Alphajet trainer aircraft uses a pitch feel system which is strictly in the category of a non-linear gearing with variable spring feel. As the latter is effected by a variable gear device which is deliberately used to tailor the tail setting to a speed change, it is included in this section. Figure 53 is a schematic of this system. The non-linear gearing is of moderate degree, with a datum shift controlled by a flap interlink. Its slope changes slowly by a factor of only about two for tail angles most commonly used for manoeuvring, and much less than that at high airspeeds. Hence there is inevitably some reduction in stick force per g with increasing g, but it ranges from negligible to mild at low speeds or high altitudes. The triple slope springbox provides good centring without an explicit breakout, and the third slope prevents the maximum stick forces from exceeding about 30 lbs at maximum g despite initial gradients of typically 8 lb/g. The special feature is the variation of the trimmed stick and tail positions for a fixed trimmer setting as the airspeed changes. The result is an apparently zero speed stability with little or no need to trim for a significant speed range, a feature much liked by the pilots.

The effective variable gearing in the Boeing 747 (§4.1.2), created by cable stretch under load, was implicit in the mechanical design. It was considered a sufficiently desirable feature to be simulated in the Boeing 777 despite its lack of cable circuits. Just such an effect was deliberately sought in the "flexible stick" concept discussed by Horikoshi. A stiff spring was incorporated in the stick of a Zero aircraft so that the stick deflection relative to the manually operated elevator was a variable depending on the aerodynamic hinge moments. Unlike many explicit variable gearings, the stick force was unaffected and remained proportional to the hinge moments. Adoption of this idea for a fully powered control system must take into account the friction, to prevent excessive stick inputs with no response, and inertia and damping, to avoid introduction of an undesirable circuit oscillatory mode.

A similar effect occurs in the McDonnell-Douglas AV-8B rudder actuation system, although its hydraulic q-feel is not the cause. Because the power actuator is located remotely from the rudder, aerodynamic hinge moments reduce the rudder deflections by as much as 40% at high dynamic pressures, effectively creating a q-gearing of sorts. The rudder is therefore doubly protected by both the q-feel and by hinge moment relief.

4.2 Roll feel

Roll artificial feel has been confined largely to variants of the simple spring. Lang/Dickinson list two early jet bombers which used q-feel, producing very heavy forces. Q-feel in the EE Lightning prototype was replaced by spring feel before flight. V-feel was available in the feel simulator range illustrating Figures 34 and 36, resembling the spring tab effect, but it is not known that any design has used this form.

4.2.1 Spring feel

One of the commonest types of roll feel spring is the strut type illustrated in Figure 29. A breakout force or multi-gradient forces are almost invariably used, increasing the feel gradient around neutral to enhance the centring characteristics. An example of the importance attached to the reduction of friction is

illustrated in Figure 50, where the strut shaft is seen running in a simple linear bearing.

The other common type is the roller/cam device. Typically this is simple and compact, illustrated by the Boeing 747 feel unit in Figure 54. The parallel trimming as shown here results in a marked asymmetry of available control authority when trim is applied. In this case the non-linear force gradients ensure that the maximum possible wheel forces are little greater than is normal with no trim offset. With typically quite small wheel or stick forces, roll trim runaway can often be held with little difficulty, and a parallel trim system cannot independently overpower the pilot's control inputs. Accordingly the trim actuation redundancy is usually of a lower level of complexity than that described in §3.2.4 for the 747, in which the pitch trim has very large independent authority.

Two examples of unusual spring arrangements are included for interest. The English Electric Lightning bottom-articulated stick was illustrated in Figure 25. The feel spring is a torsion bar, Figure 55, driven directly from the column base universal joint. This produces zero friction and no breakout force, control centring being successfully reliant on the very low circuit friction levels achieved in this aircraft. Parallel or feel trimming is used. Two other devices complete the system. A non-linear gearing (location shown in Figure 22) reduces the control gain by some 40% around neutral. A limit stop operated by a main wheel door reduces the aileron travel from ±16° to ±8° when the undercarriage is retracted.

Like its pitch control system, the F-104 roll system is fitted into exceptionally slender spaces. To achieve this the system is distributed around the airframe as shown in Figure 56. The basic feel comprises two simple tension springs in opposition, one in each wing actuator group. A roller/cam spring centring device is mounted at the base of the stick, Figure 30. The trim motor in the left wing root drives the series trim actuators in the final aileron push rods by means of a flexible drive shaft, and this also sets overall travel stops at the wing root torque tubes. There is a further solenoid operated stop at the front of the stick torque tube assembly, reducing the travel limits from ±19·5° with wheels down and/or a left/right flap difference to ±10° with wheels up and equal flap settings. In this example, trim runaway applies a permanent offset of the total control authority limits.

The SR-71 roll feel with series trim was shown in Figure 49, and is even simpler than the F-104, with an essentially linear feel spring with no explicit centring device. A manually operated stick stop is used to reduce the roll authority from ±12° to ± 7° above Mach 0·5.

4.2.2 Roll gearings

Several of the aircraft in Lang/Dickinson used non-linear gearings to reduce control sensitivity around neutral, as noted above for the EE Lightning. To restrict the authority at high speeds, some other early types used a gear change, operated by altitude, undercarriage selection or manually, or alternatively variable position stops were used (§4.2.1). The Blackburn Buccaneer used both a non-linear gearing and a pilot-operated gear change, reducing the aileron travel from ±17° to ±12° for high speeds.

The differential tail variable roll authority and roll-yaw gearing from the BAC TSR-2, with its blown-flap delta wing carrying no ailerons, is shown in Figure 57. The gearing used an electric actuator and three hydraulic piston actuators for three functions, varying the differential tail authority from ±2° at 800 knots to ± 5° at low speeds, doubling this to ±10° in the landing configuration, and actuating the pilot-selectable ratio taileron-rudder interconnect. The tailerons carried hydraulically powered geared elevators, normally locked but activated in the landing configuration. With this doubling of the aerodynamic roll power, the roll control authority was effectively varied over a range of 10:1. After rig tests revealed excessive circuit inertia at the maximum gearing, the maximum authority was in the event limited to ±8° for flight testing, which proved to be sufficient.

The Sepecat Jaguar uses a unique variant of a variable authority roll gearing in that it functions primarily as a roll-yaw interconnect, Figure 58. The differential tail action is secondary to the spoilers, providing only a relatively small rolling moment, but because of its proximity to the fin the yawing moment is considerable. The roll gearing schedule is arranged to provide yaw co-ordination to minimise sideslip in rolling manoeuvres.

Spoiler operation requires a uniquely non-linear authority gearing. For aircraft where the spoiler is the only or primary roll control, the gearing must provide an instant switch from zero to unity ratio to each spoiler as the stick passes through centre. The Sepecat Jaguar unit, known as the "crab", is shown in Figure 59(a). The circular arc slots give an additional non-linear spoiler-stick relationship, although as spoilers are usually also aerodynamically non-linear it is their combined effect that determines the total characteristic.

On many airliners, the spoilers complement the ailerons, are generally not extended within a small central range of control wheel input, and are used as speed brakes requiring roll demands to close the extended spoilers. Figure 59(b) shows one part of the complex Boeing 747 spoiler gearing distributed throughout a system of spoiler and speed brake programmers and ratio changers, powered by two central actuators and driving sixteen surface actuators. The ailerons are also programmed to reach full deflection at about half control wheel input, with the outboard ailerons locked out at high speed by a variable ratio gearing.

Such mechanical control complexity, most often found in the roll control circuits, imposes substantial design, development and maintenance cost overheads. This burden is in itself a strong justification for electrically signalled spoilers as employed in the Boeing 767 and Airbus 310 airliners, prior to the introduction of full fly by wire. In the fly-by-wire Panavia Tornado, the spoilers are excluded from the mechanical reversion system, which comprises only an increased authority differential tailplane with its own non-linear roll gearing.

4.2.3 Bobweights

Bobweights reacting to rolling velocity were used to supplement the spring feel on one fighter/ light bomber (Lang/Dickinson). This may have been associated with the problem of roll/pitch divergence or autorotation in negative g rapid rolling, common to inertially slender aircraft in the early jet period. Typically it resulted in restrictions on allowable low-g rolling manoeuvres. This solution, its success depending on uncertain pilot strength levels, appears to have been unsuccessful as it is not known in other designs. A bobweight system was investigated for the English Electric Lightning, with a non-linear linkage arranged to provide stick forces proportional to roll rate squared and stick deflection cubed, but it was not adopted.

Although this was not an explicit feel system device, a bobweight was used successfully in the North American B-70 supersonic bomber to augment the dihedral effect (Wolowicz). While roll acceleration sensing plays no useful part in roll feel or augmentation, it should be remembered that the pilot's arm and stick masses form a very effective acceleration bobweight against which adequate counter-balance is seldom possible. This has been a contributory factor in some roll ratchet problems, as discussed in Gibson (1995), van Paassen (1990) and in Part 2. While the underlying cause is likely to be higher order sytem dynamics for which the appropriate remedy should be obvious, and in at least one case small amplitude spoiler aerodynamic non-linearity was a major influence, the simple feel device of a circuit viscous damper can be extremely beneficial here.

4.3 Yaw feel

Although the rudder is mostly a secondary control which is frequently not used to much extent in up-and-away flight, it has usually been limited in authority by some means at higher airspeeds to prevent overstressing by excessive inputs. Rudder arti-

ficial feel has utilised a range of devices including q feel, V-cubed feel, spring feel, variable ratio gearings, non-linear gearings and variable stops, alone or in combinations. A number of types in Lang/Dickinson had only a simple spring feel with constant authority. Examples of several types are given here.

4.3.1 Q-feel

Figure 60 shows the single piston rudder q-feel unit from the English Electric Lightning. Auxiliary spring feel was provided by four springs acting in tension and compression on the feel unit, coupled with a second non-linear spring unit. The q-feel, supplied from the pitch feel simulator with Mach cut-off, was designed to the U.K. fin design "100 lbs fishtail at the (unaugmented) dutch roll frequency" and the "150 lbs rudder deflected and held" pedal force cases. This was much too heavy for approach and landing speeds, where it was shut off and only the spring feel was used. The spring units also provided emergency back-up for the simplex q-feel. The trim was of the parallel type.

Q-feel was also used on the BAC TSR-2, without Mach cut-off because of its all-moving fin. As its design limit speed was 800 knots CAS, the pedal force gradient was very large at high speeds. Duplex feel units were used with no spring reversion, though the pedal forces were again rather high at low speeds because of the influence of the design cases. An example of the travel restriction effected by q feel is the 150 lbs pedal load for 2·5° rudder at maximum EAS.

4.3.2 Spring feel

Figure 61 shows the Lockheed F-104 rudder roller/cam spring feel and travel stop system. The rudder travel limits are ±20° with landing gear down and/or different left-right flap settings, and ±6° with landing gear up and equal flap settings. The trim is of the series type, acting on the feedback linkage in the rudder servo assembly.

The Lockheed SR-71 twin rudder system uses pure spring feel in a unique arrangement, Figure 62. Each rudder actuation system, controlled by an independent cable and rod drive from the pedals, has its own series trim actuator incorporating within its casing a feel spring providing half the total feel. Any discrepancy between the left and right rudder trim angle is indicated to the pilot, who can eliminate it by a synchroniser switch controlling the right hand actuator separately. The pilot operated stop lever which controls the roll authority (§4.2.1) also reduces the pedal travel authority from ±20° to ±9° above Mach 0·5. The pedal gearing is linear up to this lower limit and increases gradually for larger angles, so that 2 inches travel produces 10° rudder but only 3¼ inches is need for 20°. Pedal forces remain proportional to pedal travel, indicating that the non-linearity arises within the rudder actuation drive linkages.

Figure 63 shows features of the Boeing 747 rudder roller/cam spring feel. The trim is provided by a screwjack driven by cables from the pilot's trim wheel, and is of the parallel type. Downstream of the feel unit, a ratio changer or variable gearing in the input linkages to the upper and lower rudder actuation groups alters the rudder travel from ±25° at low speed to a minimum of ±1·3° at high speed, in effect a q-gearing in which the pedal feel stiffness and travel remain constant. The parallel trim range is 16/25 of the full pedal range, a fixed trim wheel setting producing a rudder offset between 16° and 0·83° in a similar manner.

Figure 64 shows the Sepecat Jaguar rudder feel spring and parallel trim system with ratio changer. The latter, although in principle a fully variable gearing, is used simply as a two-position system with a high and a low ratio. The high ratio of ± 21° rudder is selected automatically when the undercarriage is down or when the differential tail gearing is set to its maximum, and the low ratio of ±7° is selected when the undercarriage is raised. The pilot can select these by a switch if the auto-system fails, the ratio being shown on an indicator. The trim range is 45% of the full travel.

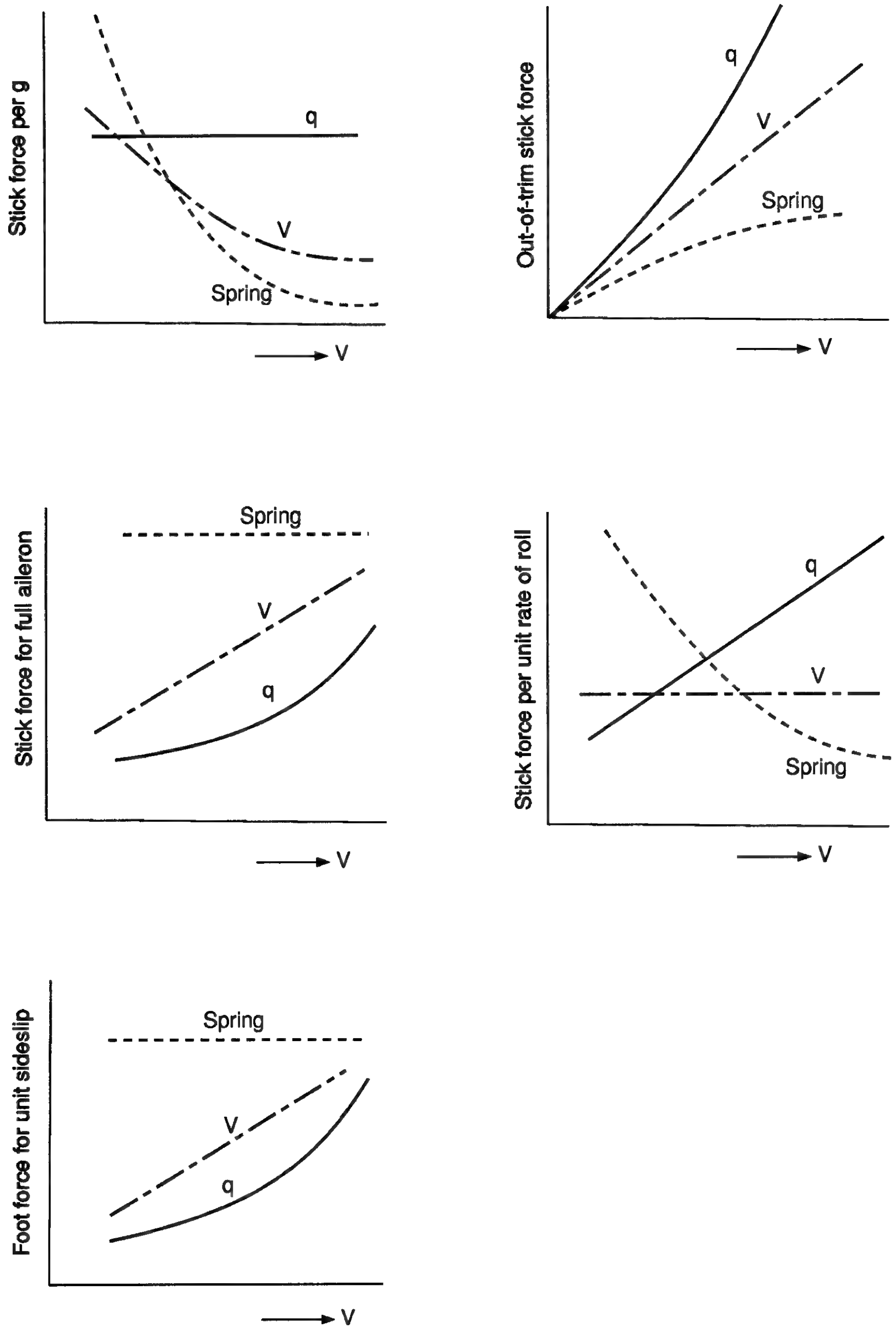


Figure 28 Some general characteristics of spring, V and q feel

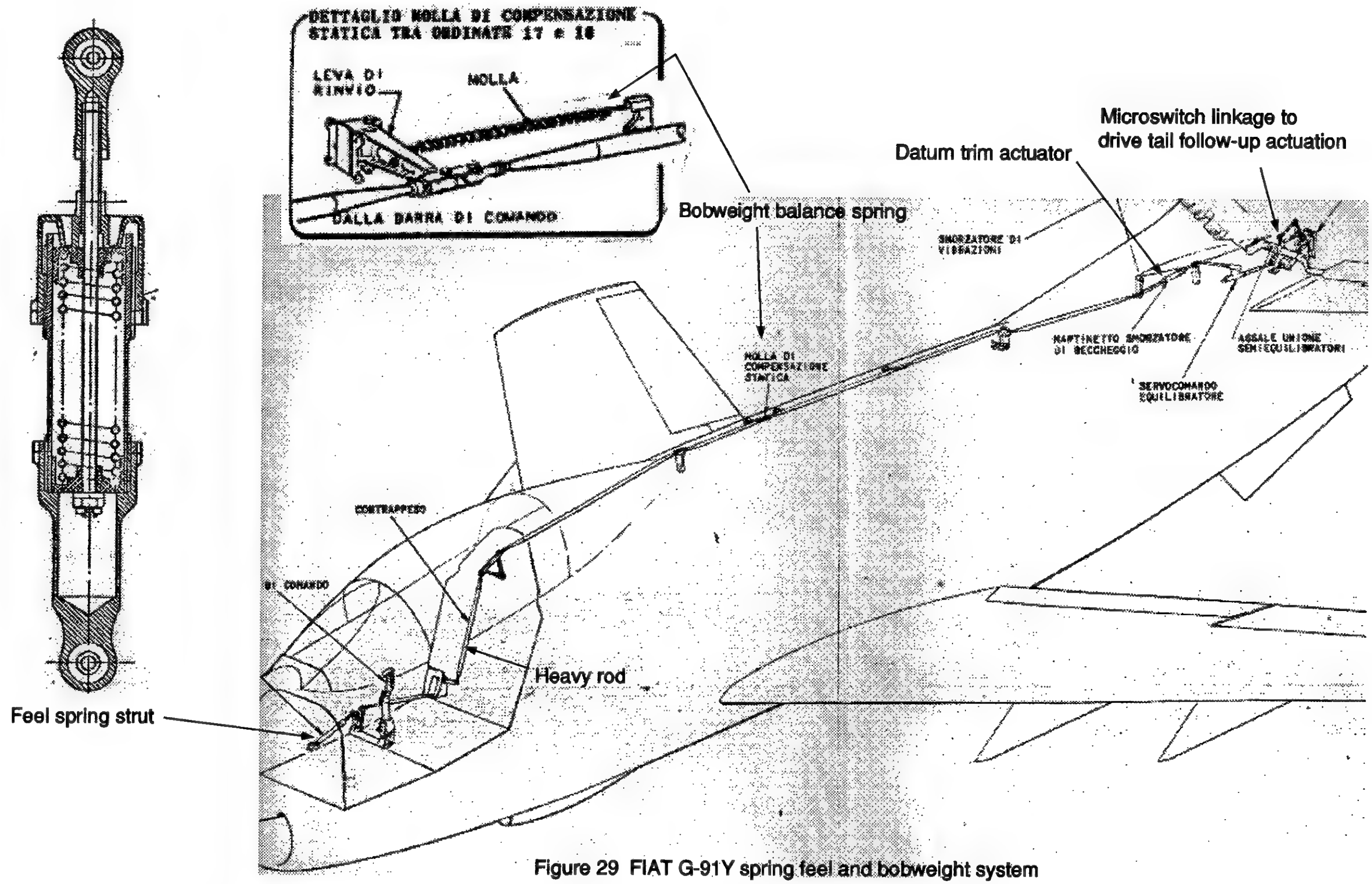


Figure 29 FIAT G-91Y spring feel and bobweight system

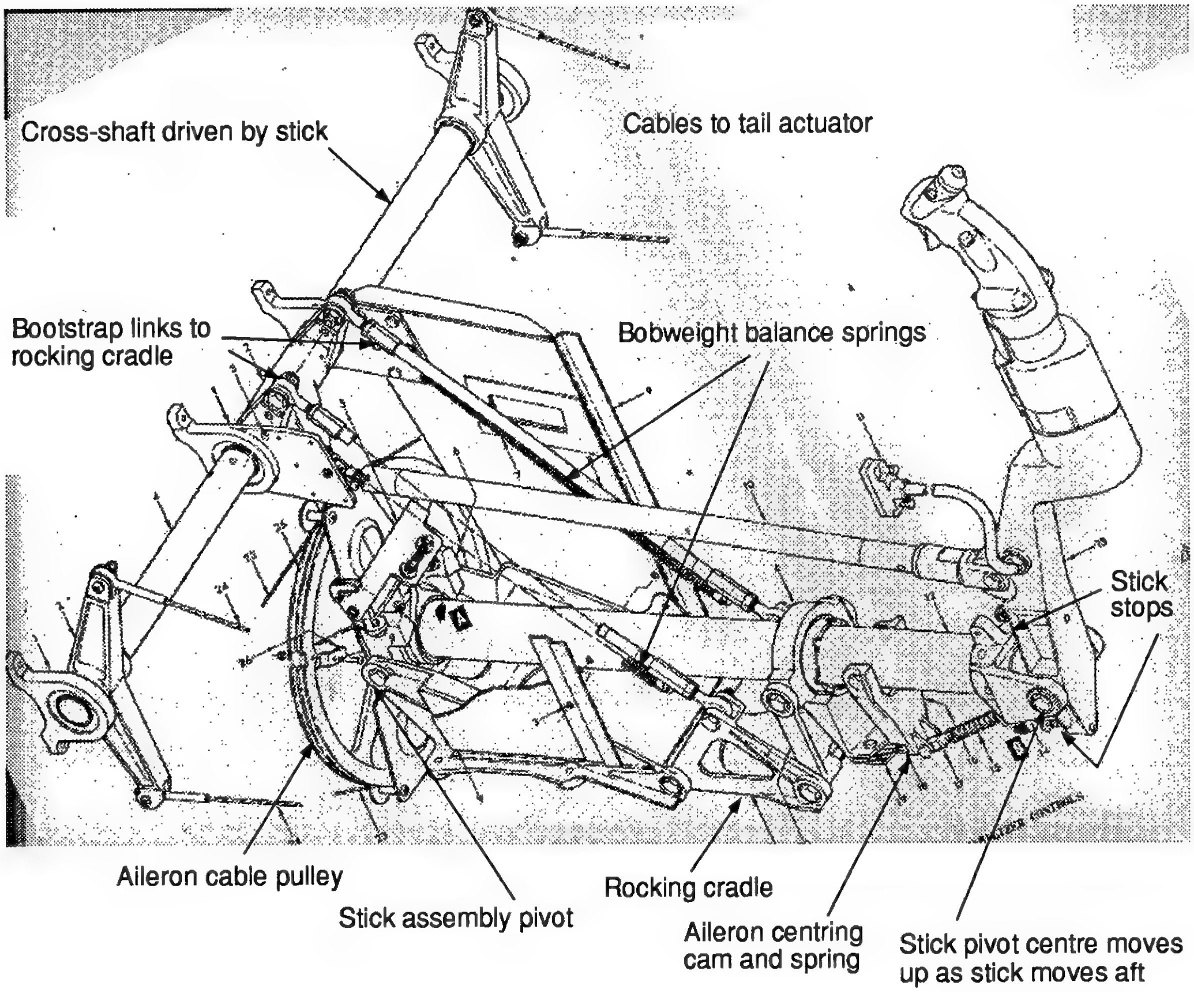


Figure 30 Lockheed F-104 integrated stick and bobweight

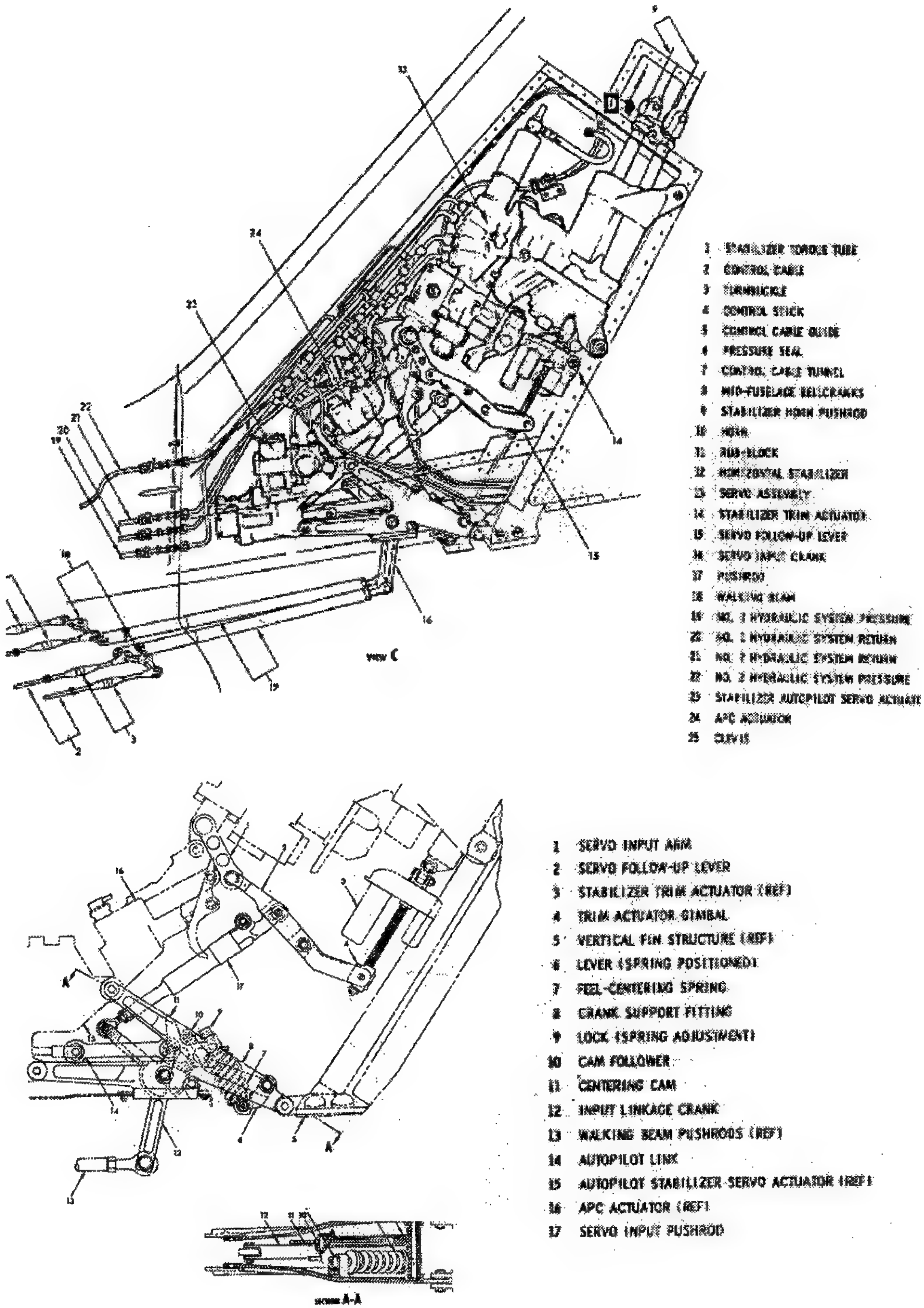
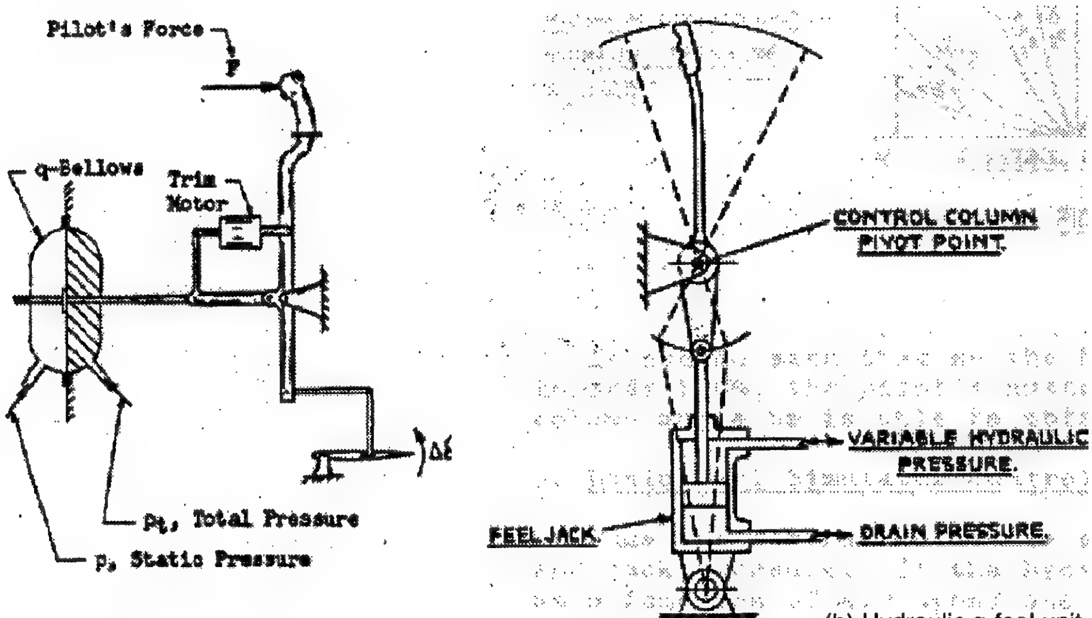


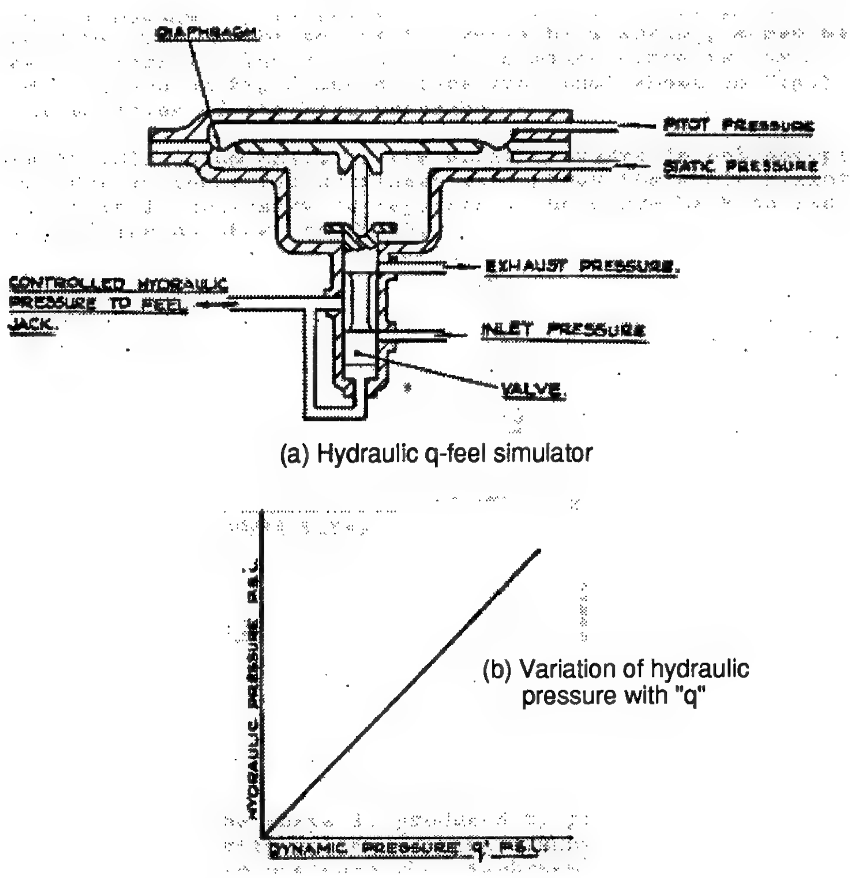
Figure 31 F-104 spring feel and tail control group



(a) The q-bellows

(b) Hydraulic q-feel unit

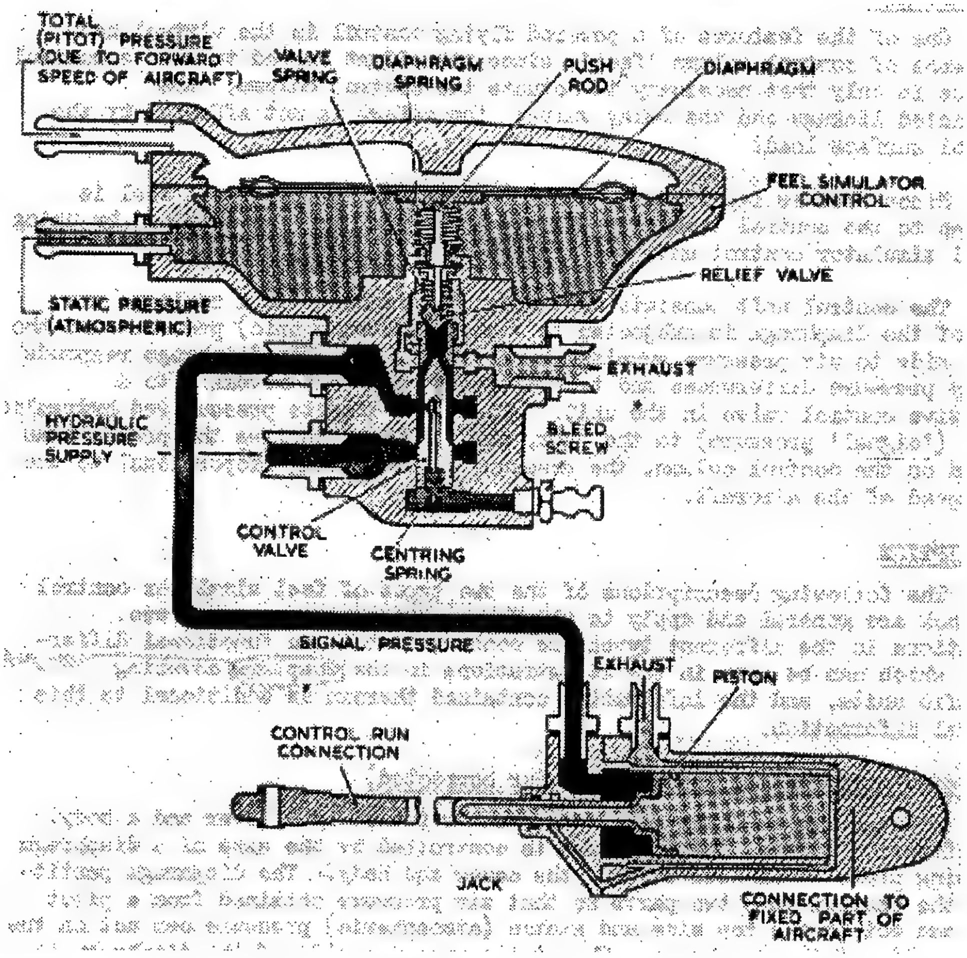
Figure 32 Basic q-feel principle



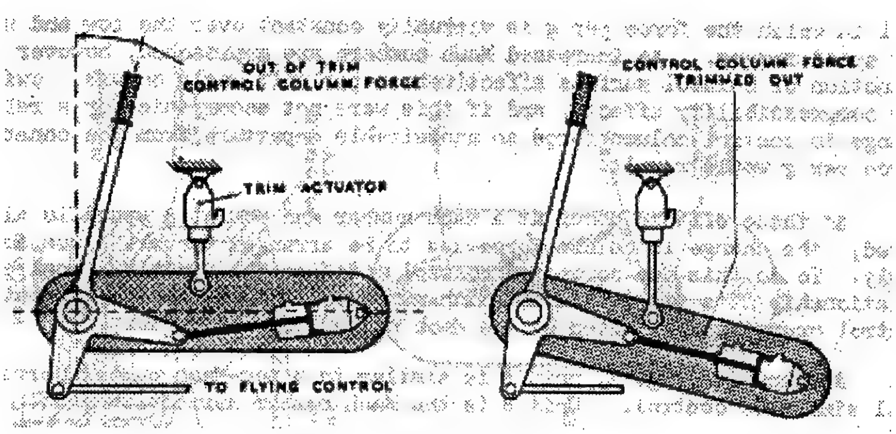
(a) Hydraulic q-feel simulator

(b) Variation of hydraulic pressure with "q"

Figure 33 Hydraulic simulation of dynamic pressure



(a) Q-feel simulator and feel jack details



(b) Feel trimming method

Figure 34 Complete q-feel system

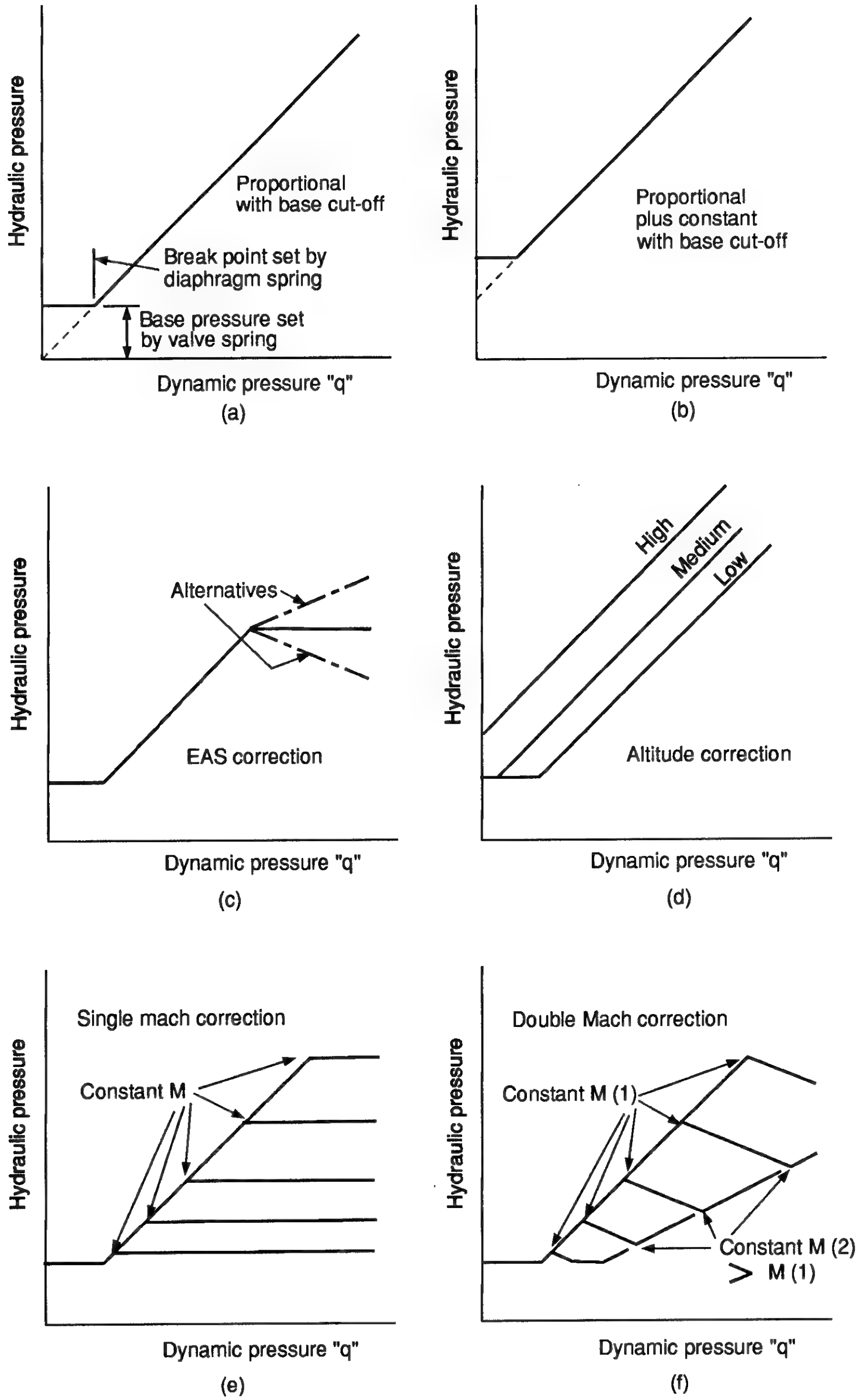
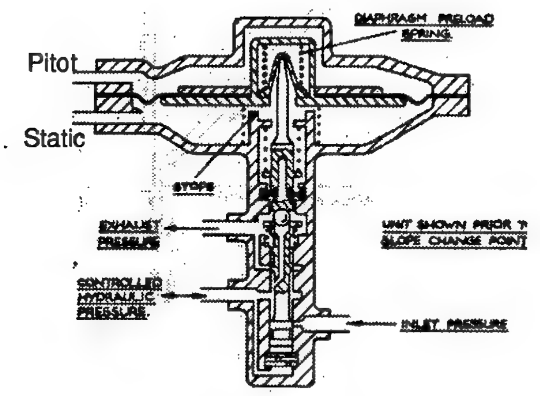
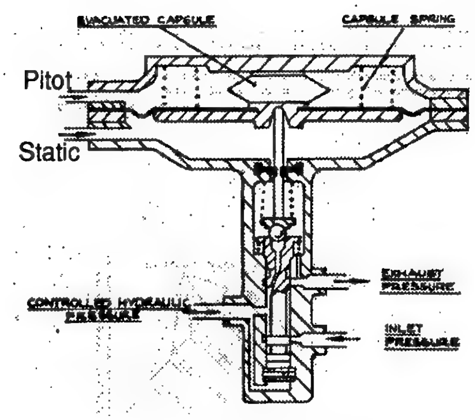


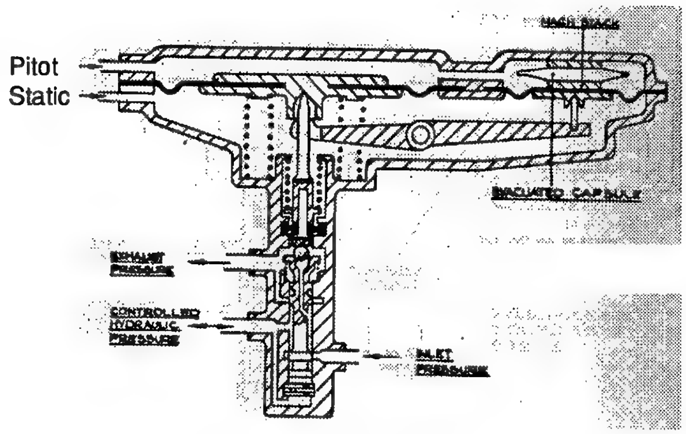
Figure 35 Feel simulation variations



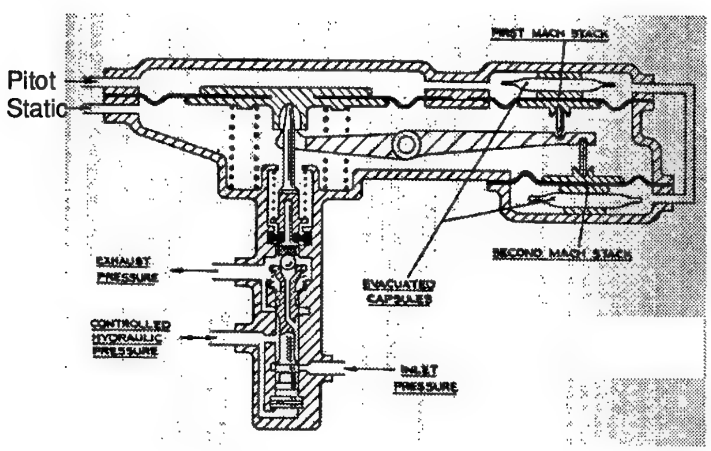
(a) EAS correction
(second diaphragm required for finite slope after the cut-off point)



(b) Altitude correction



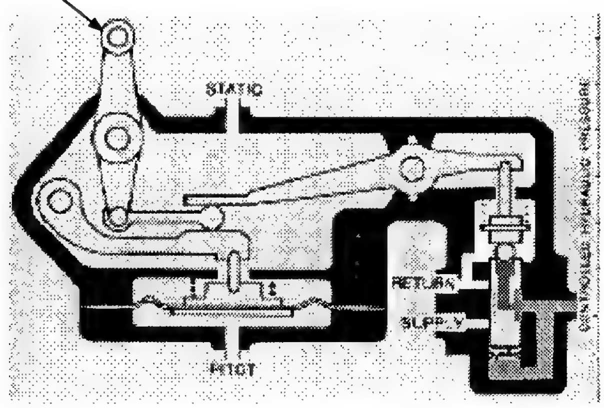
(c) Single Mach correction



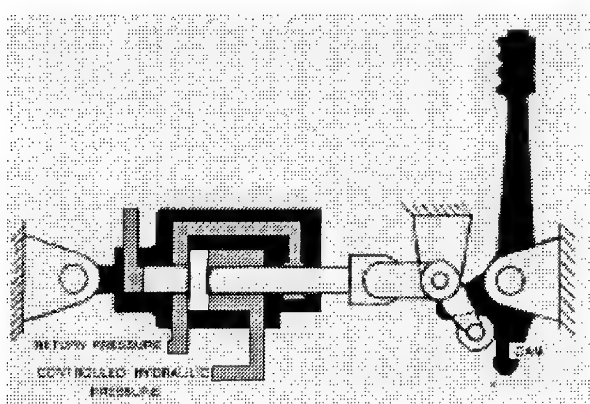
(d) Double Mach correction

Figure 36 (a - d) Feel simulator correction schematics

Desired mechanical, electro-mechanical or other input

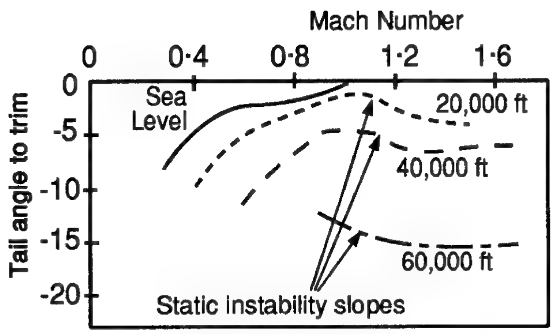


(e) Adjustment by mechanical input

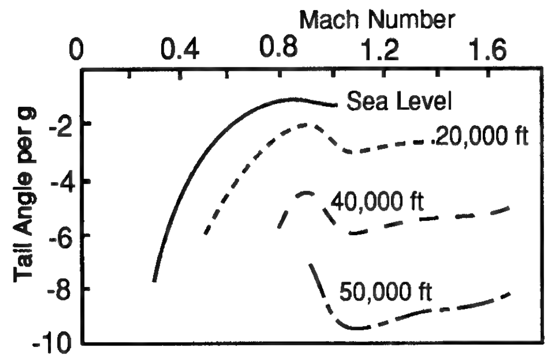


(f) Non-linear force gradient adjustment

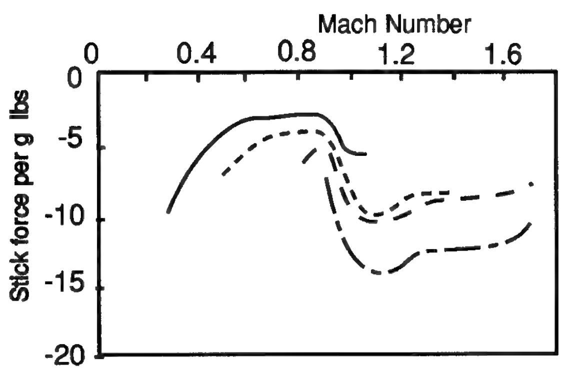
Figure 36 (e, f) Feel simulator correction schematics



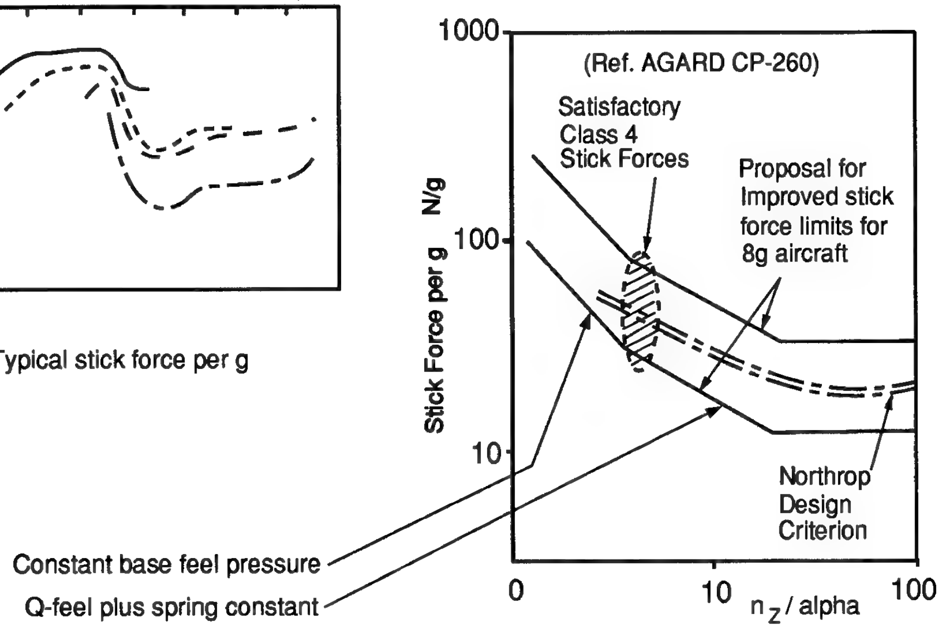
(a) Typical tail angles to trim



(b) Typical tail angles per g



(c) Typical stick force per g



(e) Feel simulation adjustments

(d) Stick force per g proposal

Figure 37 Effect of Mach cut-off and base feel

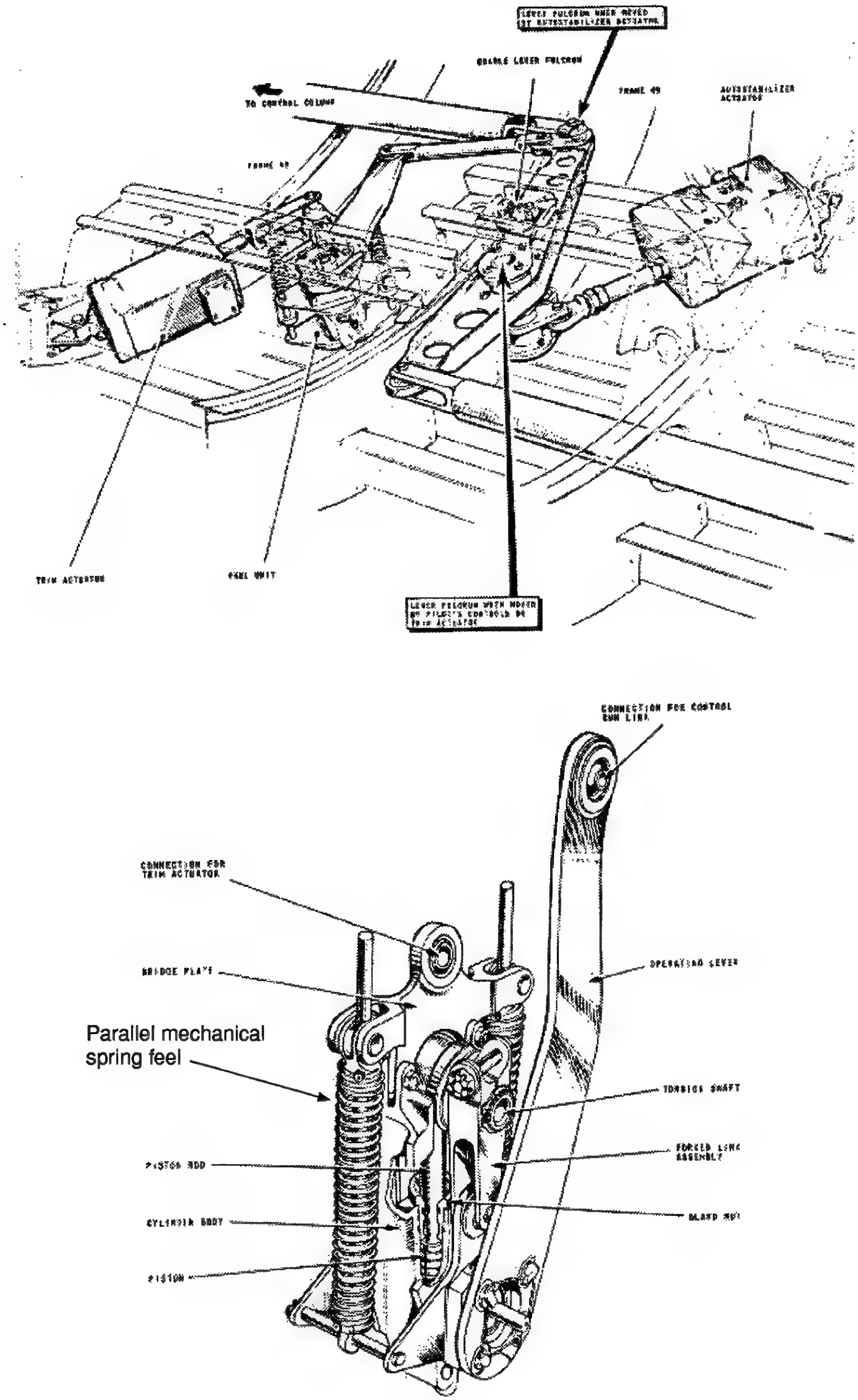
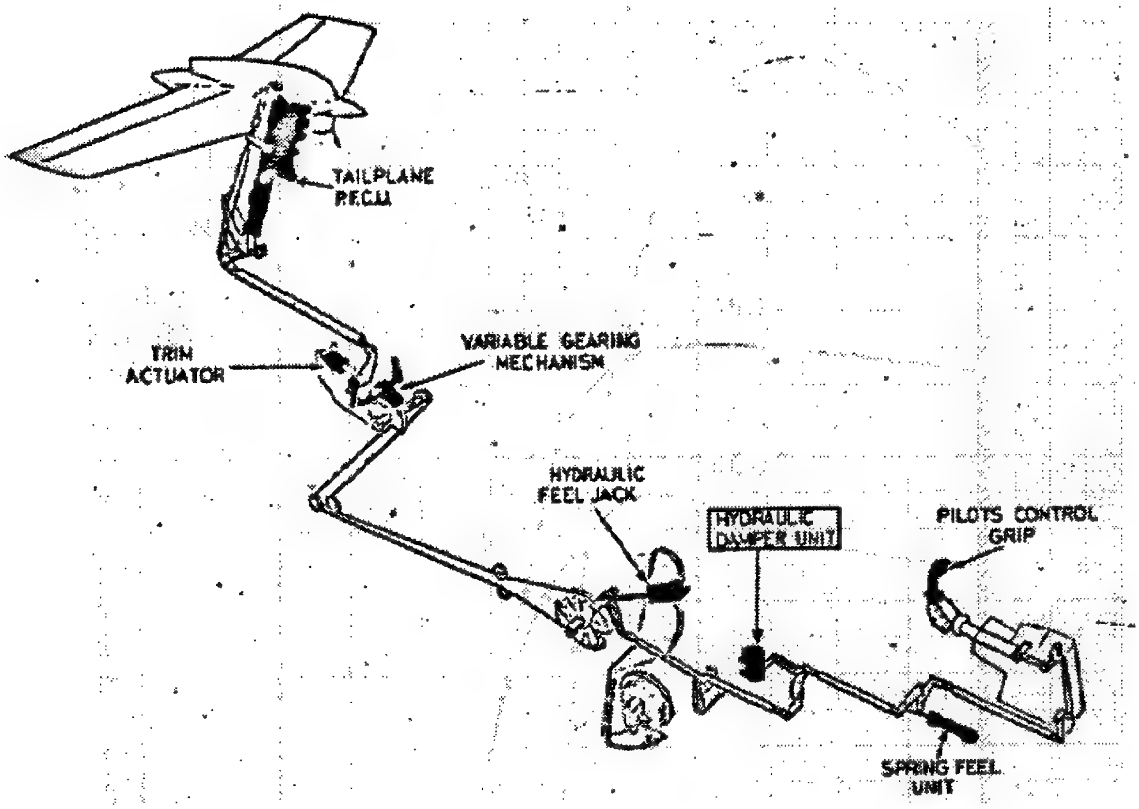
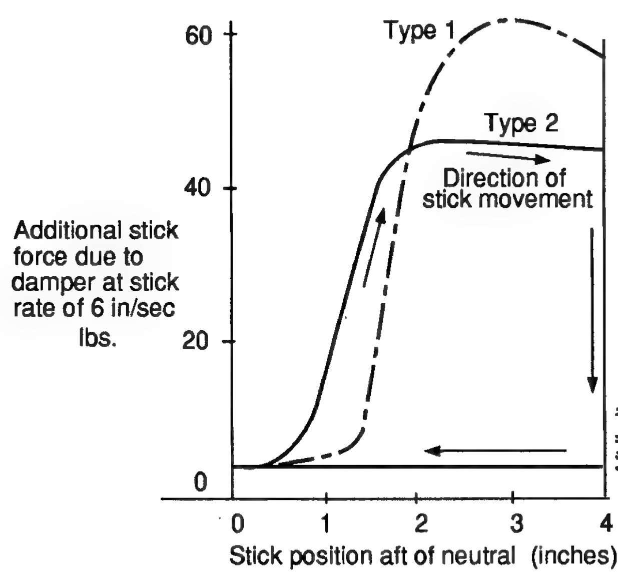


Figure 38 Lightning pitch feel installation and jack



(a) Pitch system schematic



(b) Experimental anti-snatch damper

Figure 39 Blackburn Buccaneer pitch feel and control system

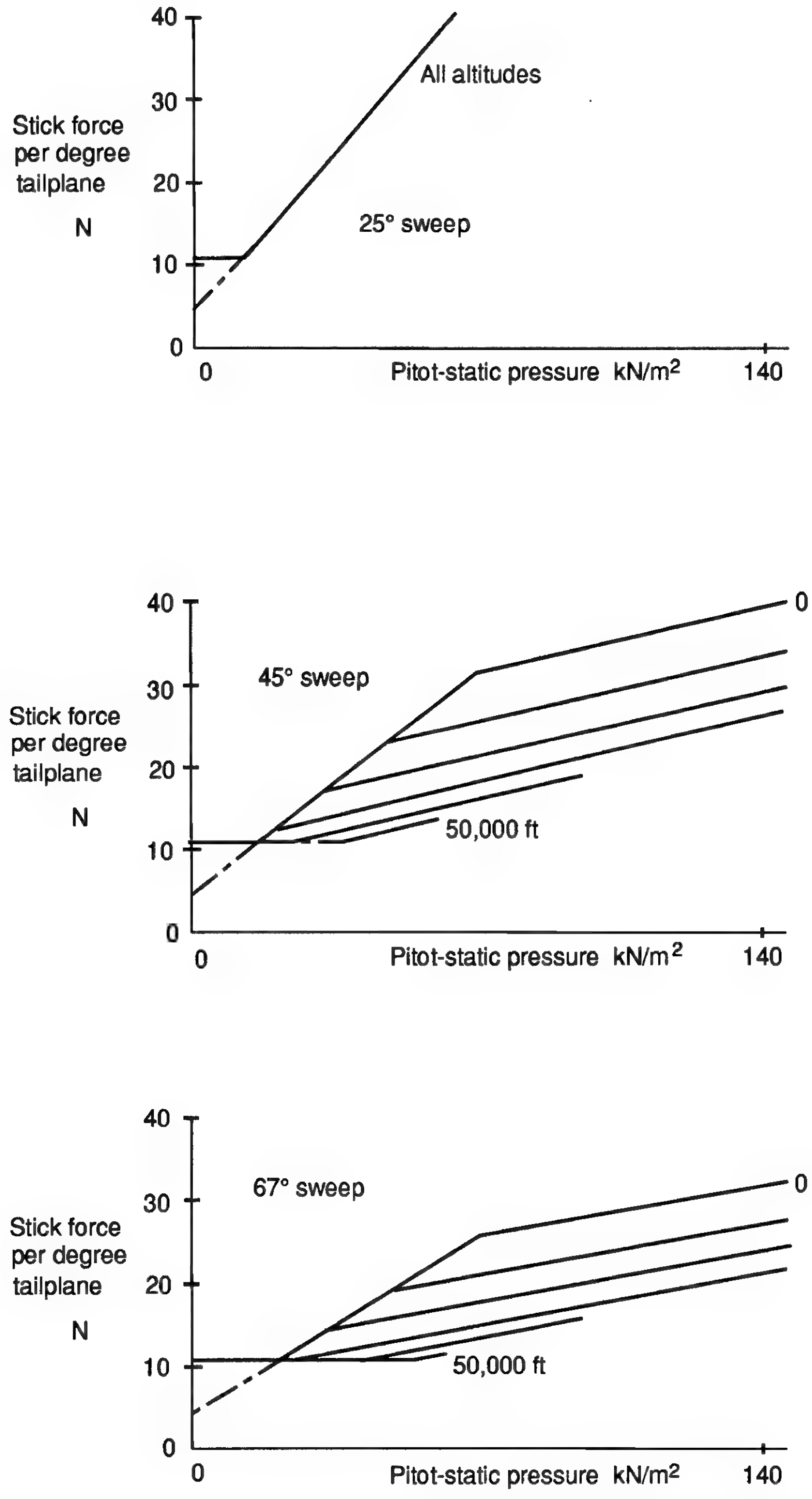
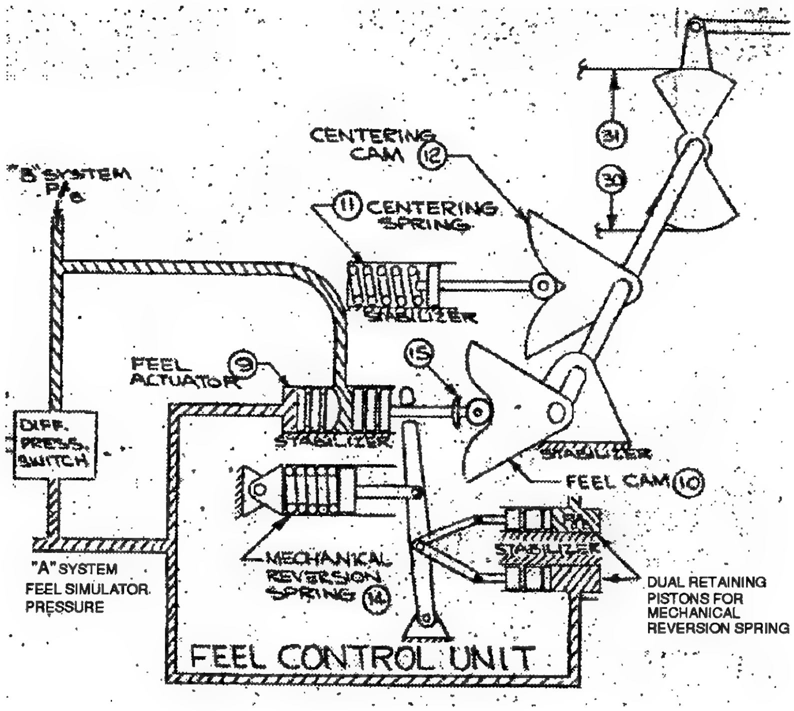
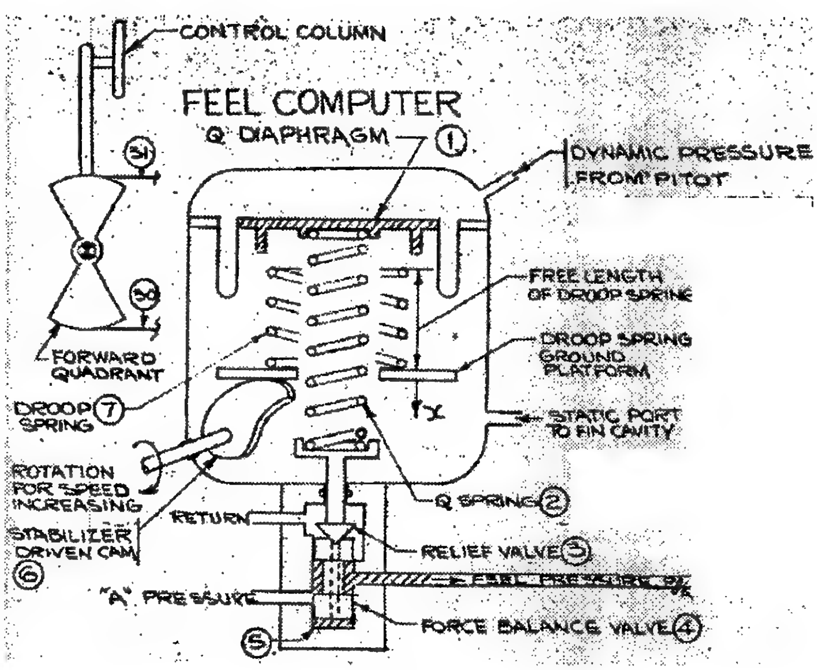


Figure 40 Panavia Tornado pitch feel force variation with sweep

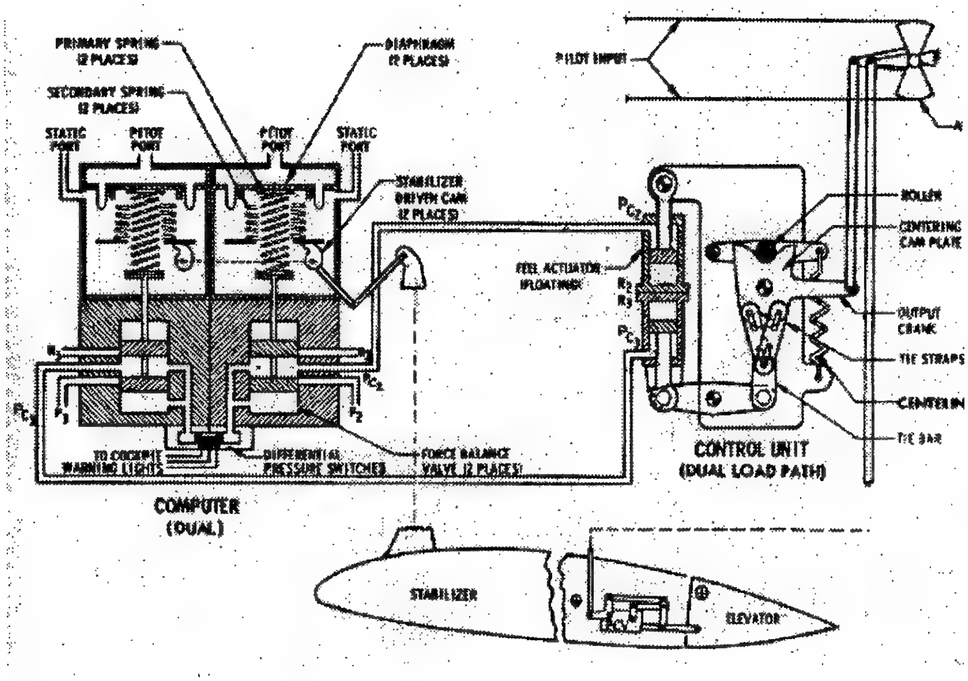


(a) Schematic of pitch feel unit

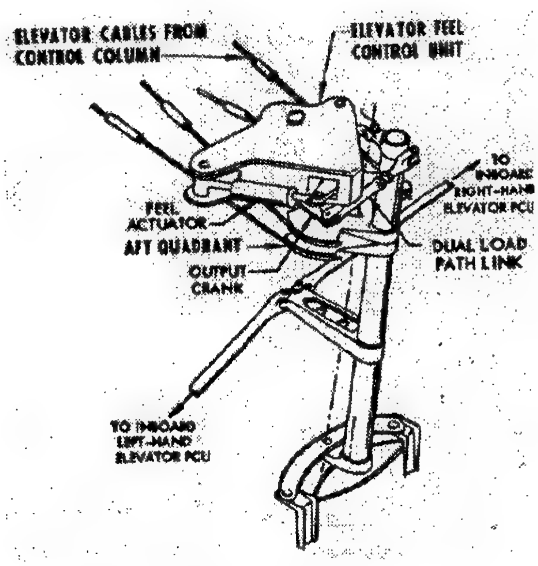


(b) Schematic of feel simulator

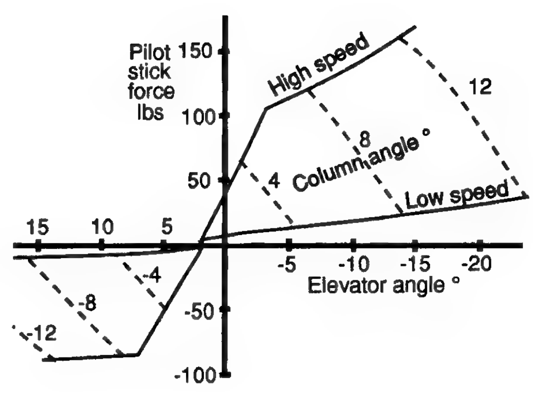
Figure 41 Boeing 727 pitch q-feel system



(a) Pitch feel system components

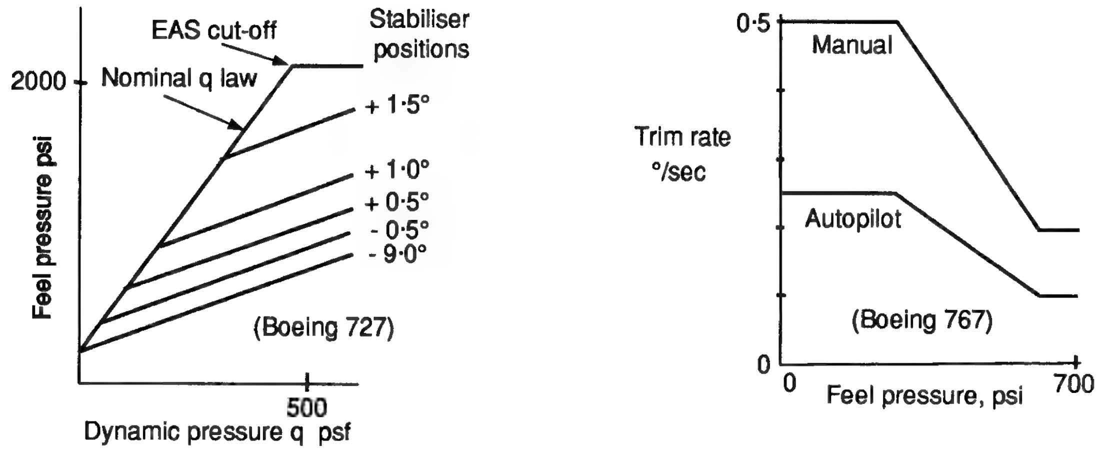


(b) Feel unit mounting on fuselage structure



(c) Effects of tie straps and cable stretch

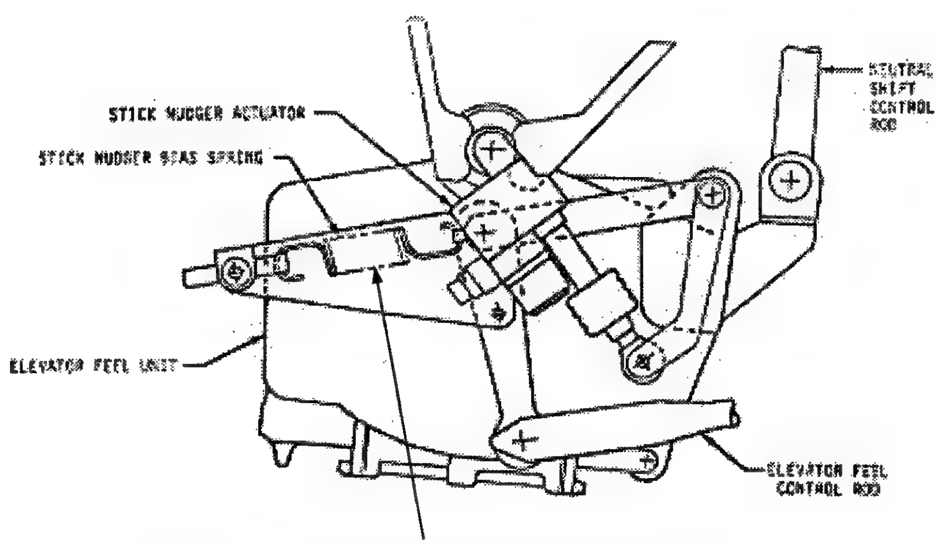
Figure 42 Boeing 747 pitch feel unit schematic



(a) Influence of stabiliser position on pitch feel simulator pressure

(b) Influence of pitch feel simulator pressure on pitch trim rates

Figure 43 Examples of inter-related pitch control parameters



Operation of nudger actuator shifts spring line of action away from lever pivot, exerting a stick-forward torque.

Figure 44 Boeing 767 pitch feel stick nudger

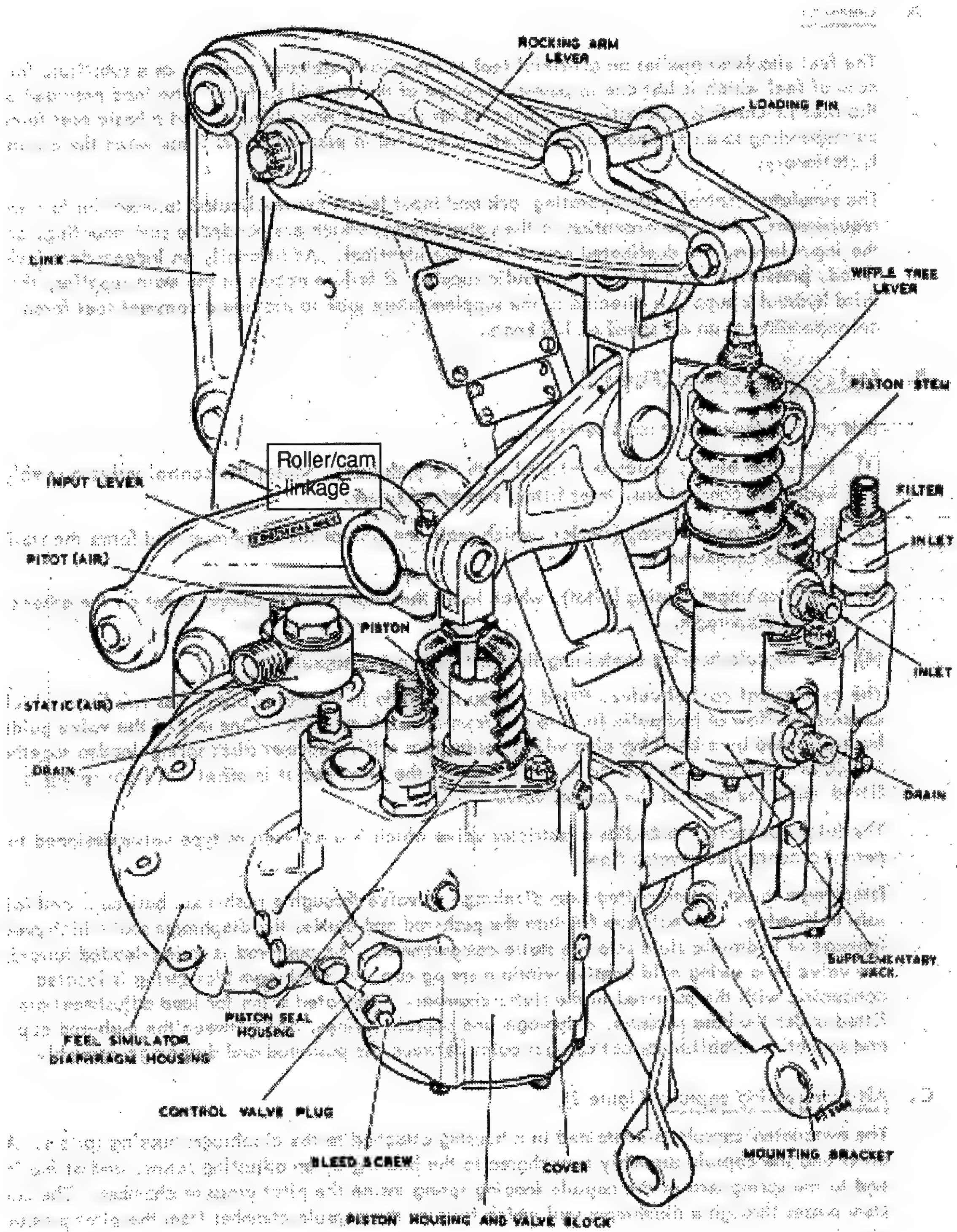
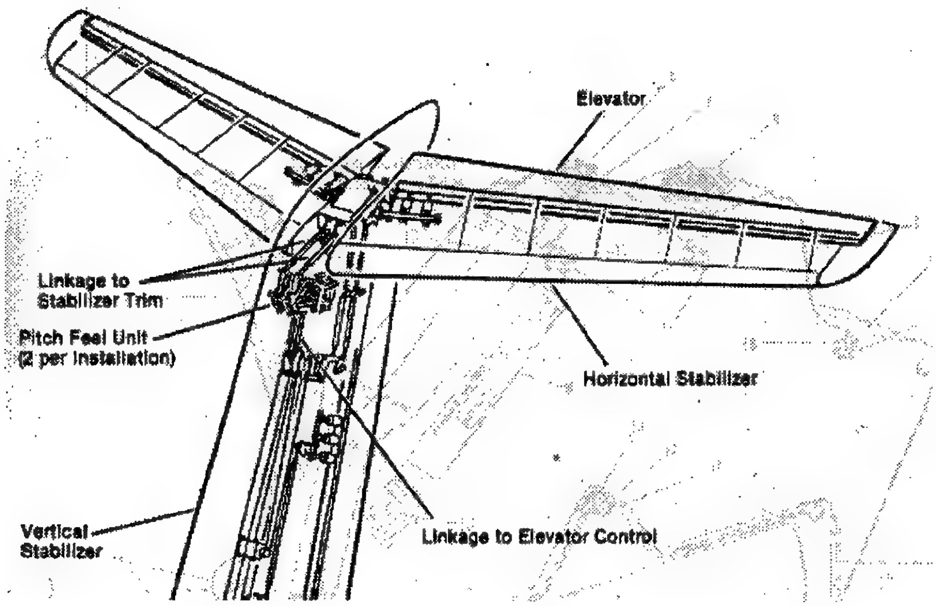
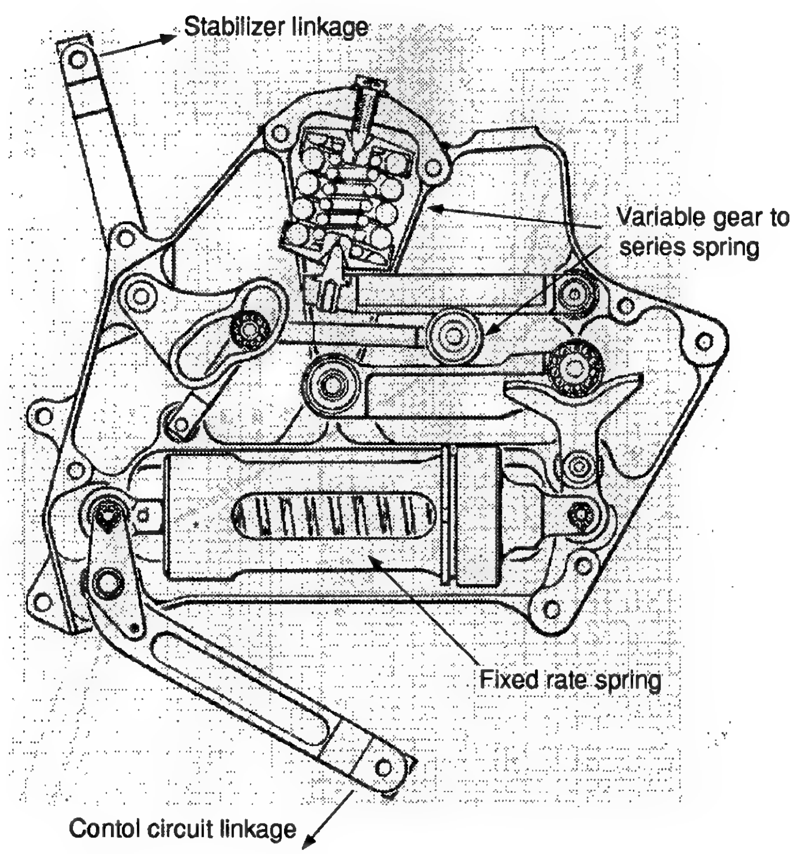


Figure 45 BAC 111 Duplicated pitch q-feel with emergency back-up

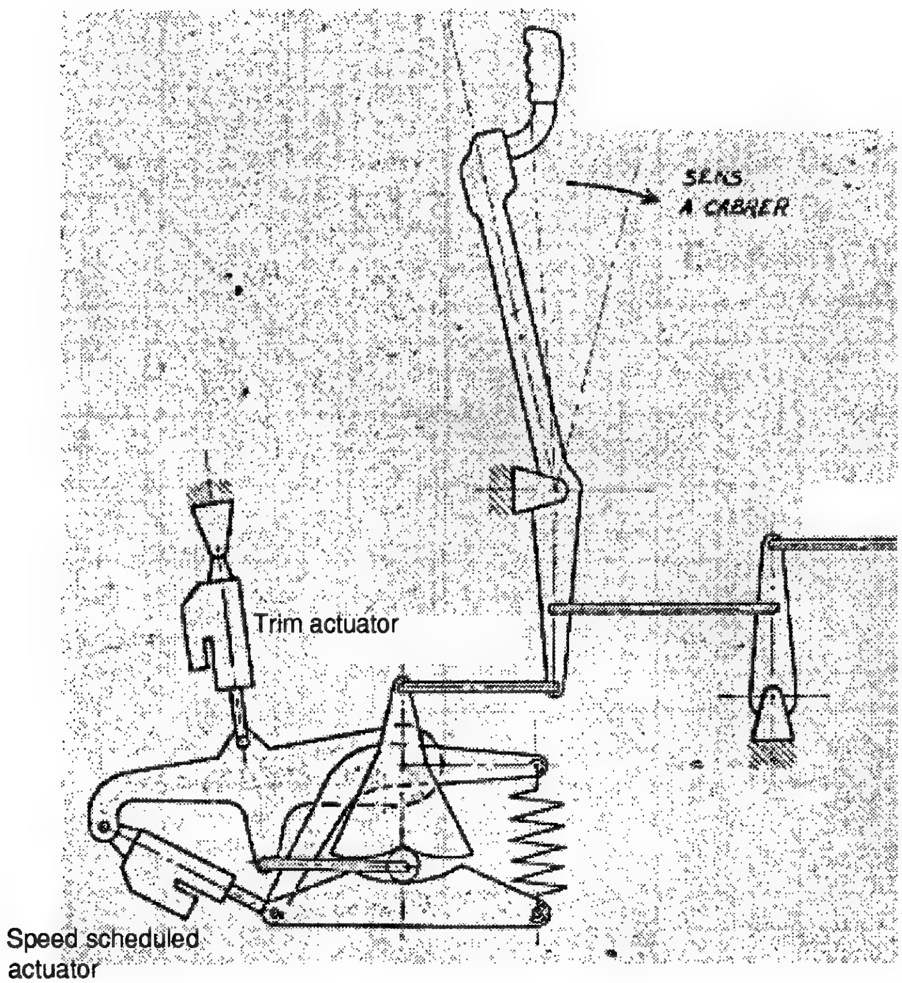


(a) Feel unit installation

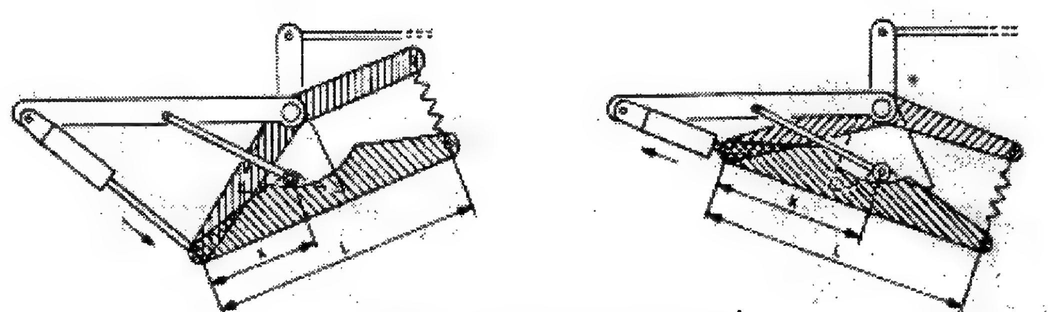


(b) Spring feel unit

Figure 46 Canadair CL 600 pitch spring feel unit



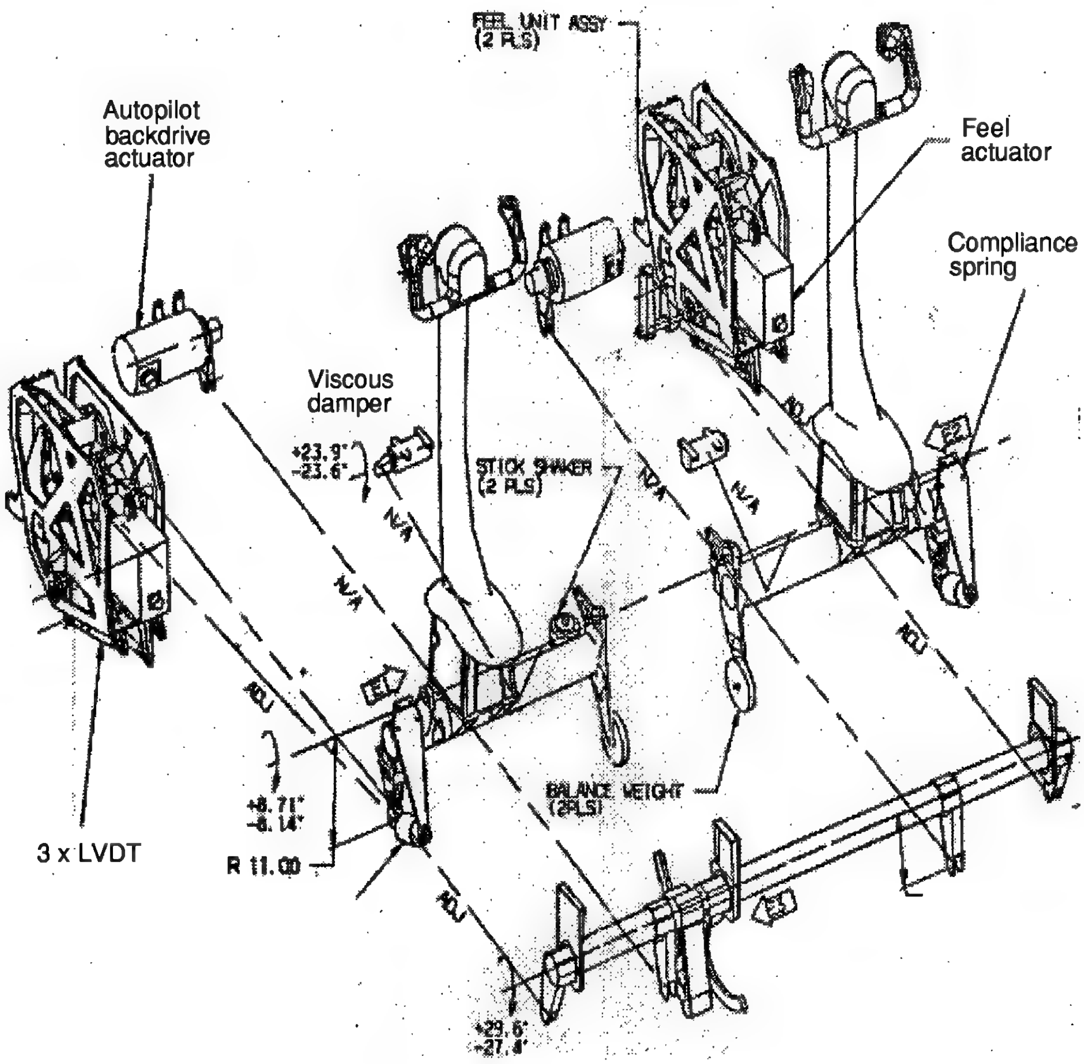
(a) AJAX feel unit schematic



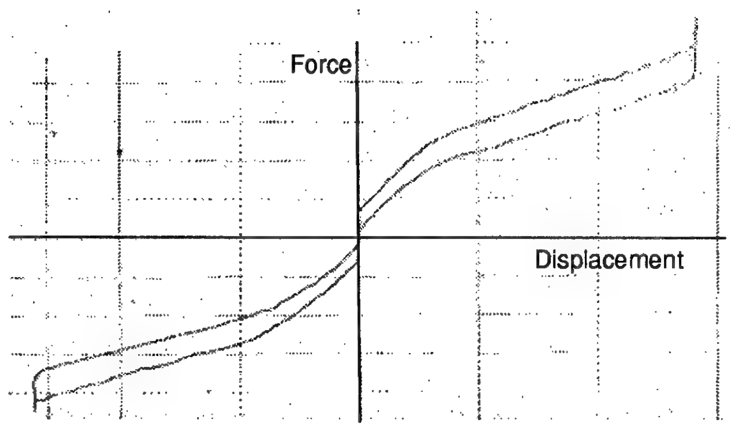
Effective stiffness proportional to $\frac{L}{X}$

(b) Principle of variable feel gradient

Figure 47 Sepecat Jaguar "Ajax" pitch feel schematic

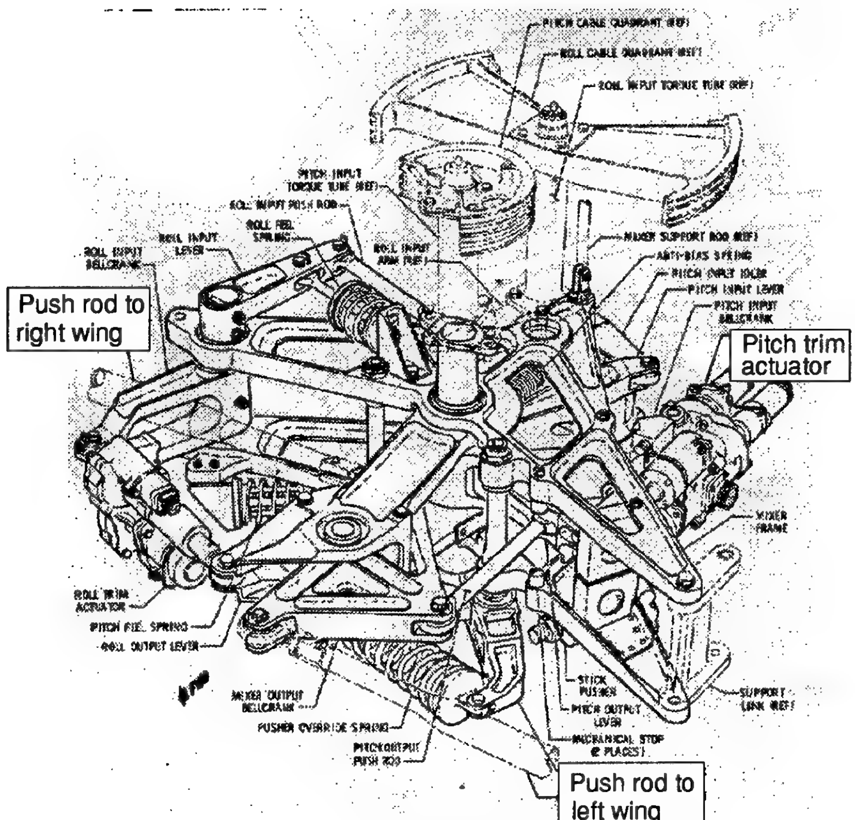


(a) Pitch circuit layout

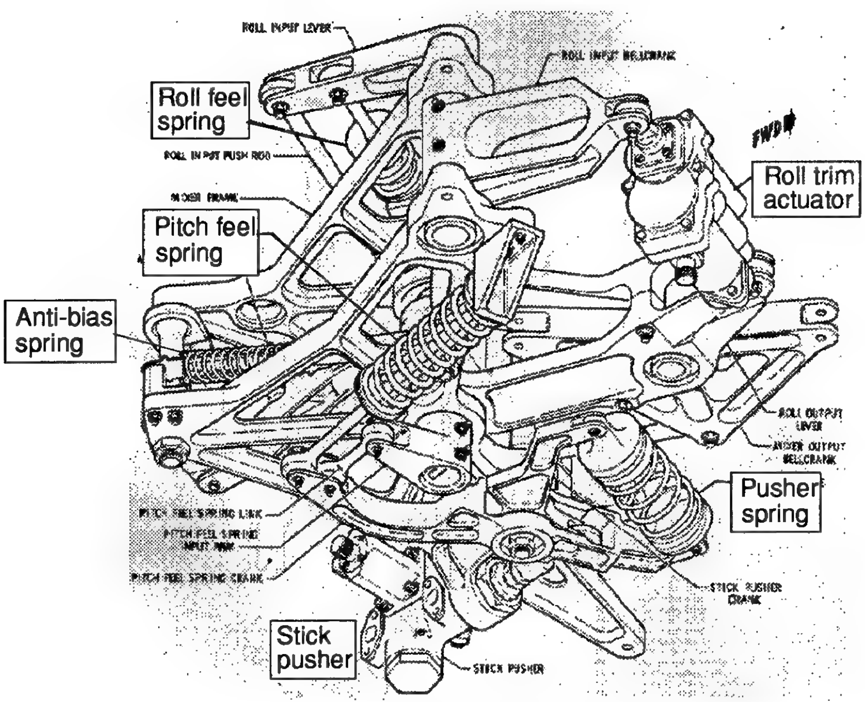


(b) Conventional column force-displacement test results

Figure 48 Boeing 777 pitch control and feel

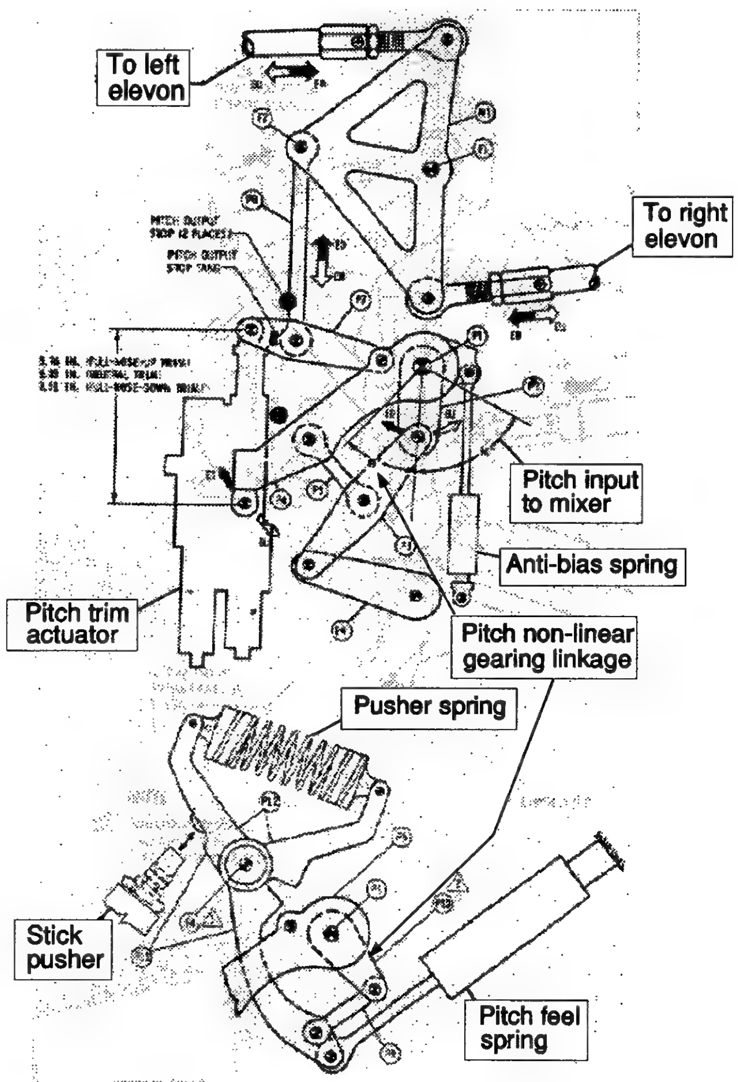


View from above

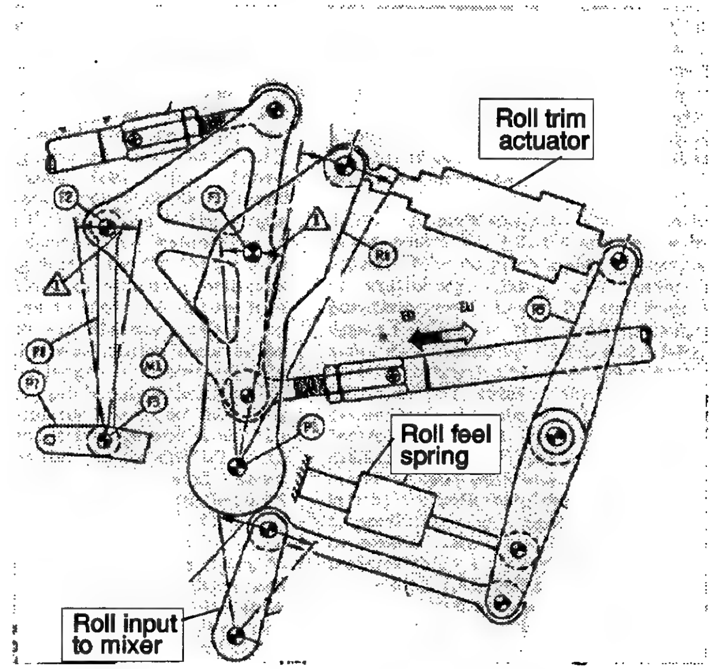


View from underneath

Figure 49 Lockheed SR-71 pitch-roll elevon mixer and feel system



Pitch linkage



Roll linkage

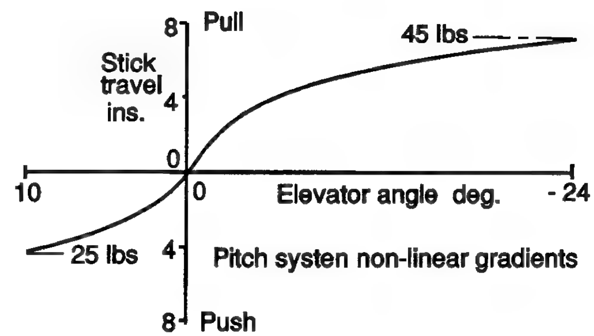


Figure 49 (cont.) Lockheed SR-71 elevon mixer functions

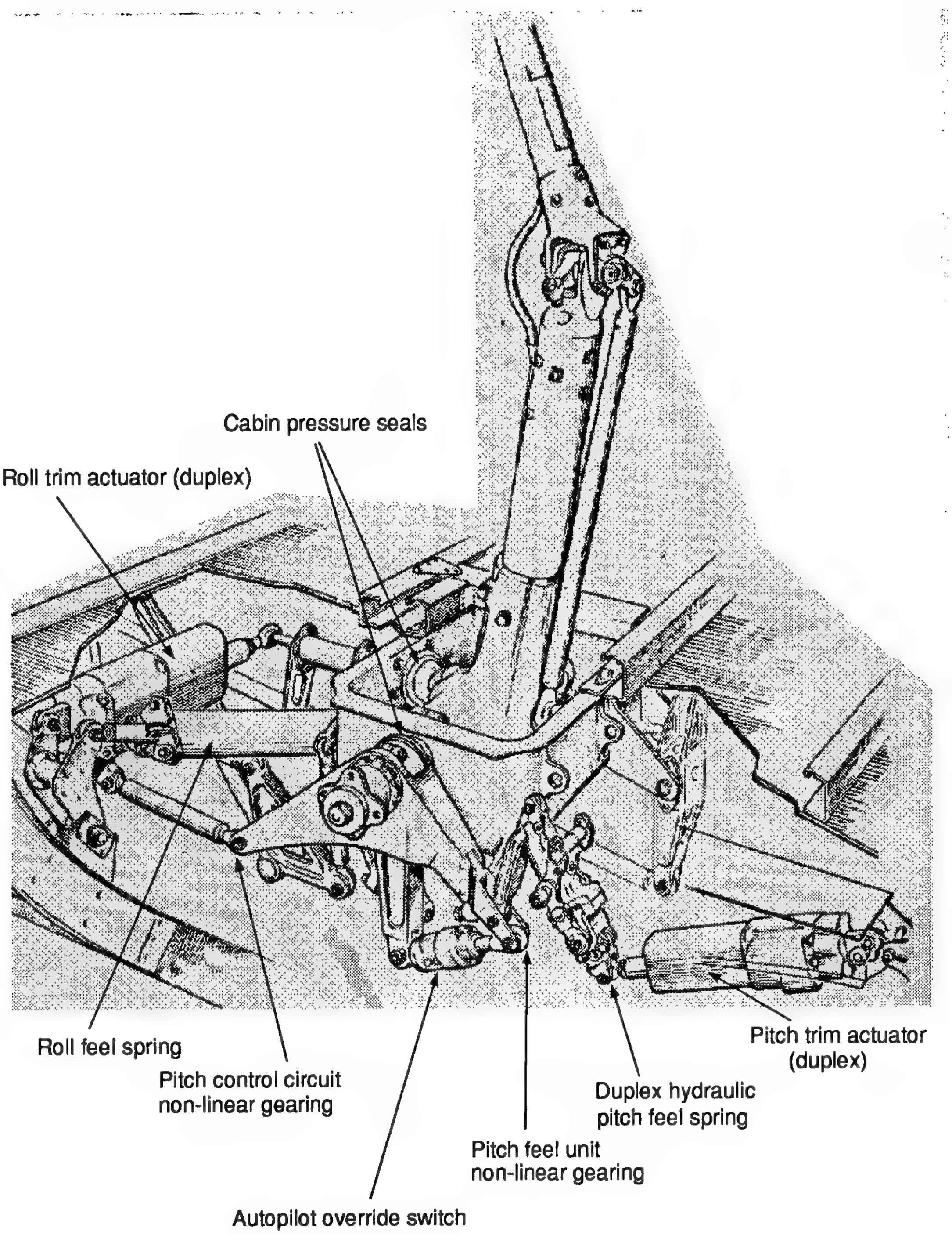
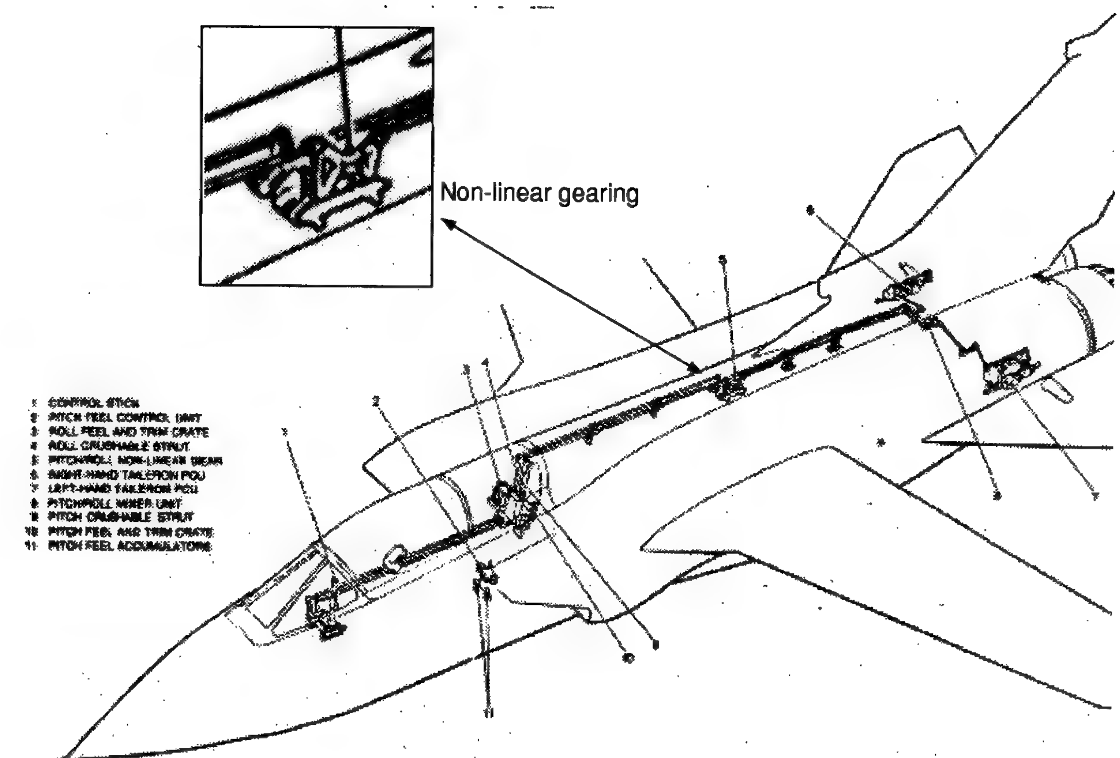
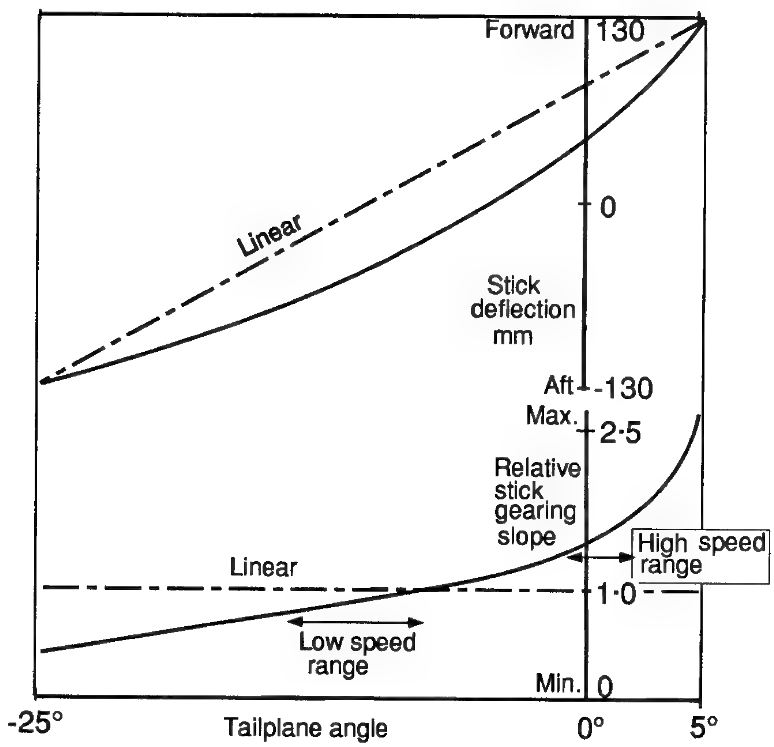


Figure 50 TSR-2 stick feel and nonlinear gearing system

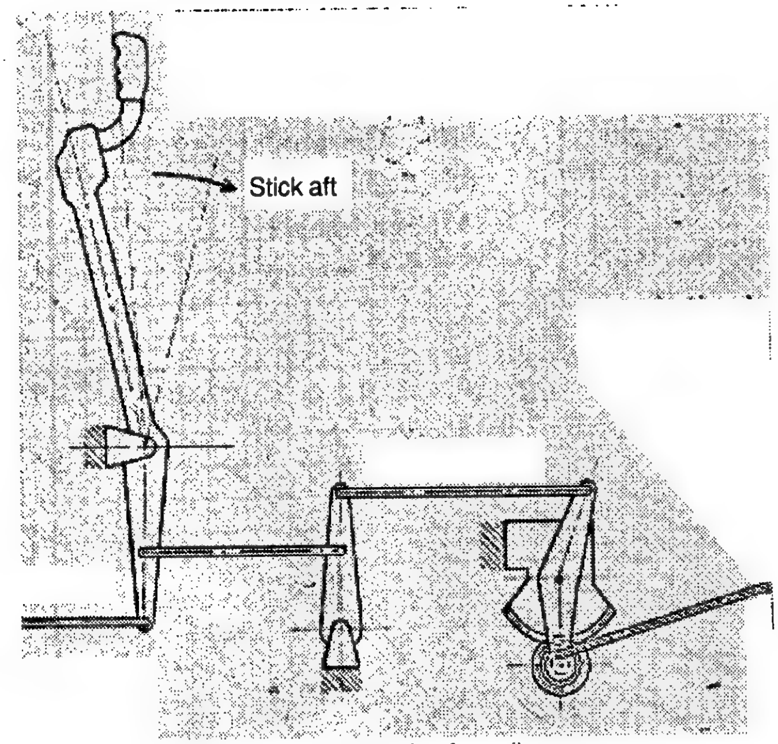


(a) Tornado mechanical reversion control circuits

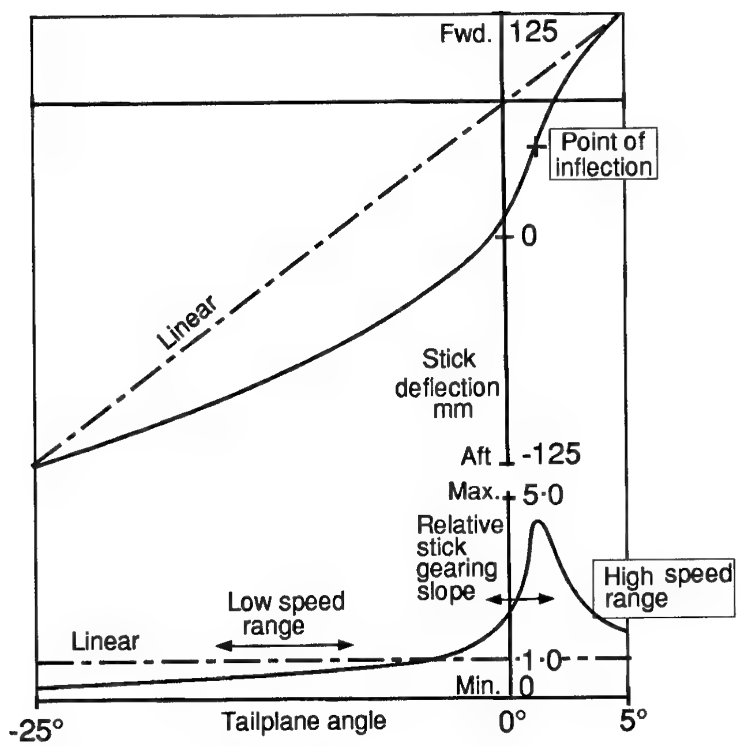


(b) Stick travel and gearing slopes

Figure 51 Non-linear stick gearing (monotonic)



(a) Example schematic of non-linear gear



(b) Stick travel and gearing slopes

Figure 52 Non-linear stick gearing (non-monotonic)

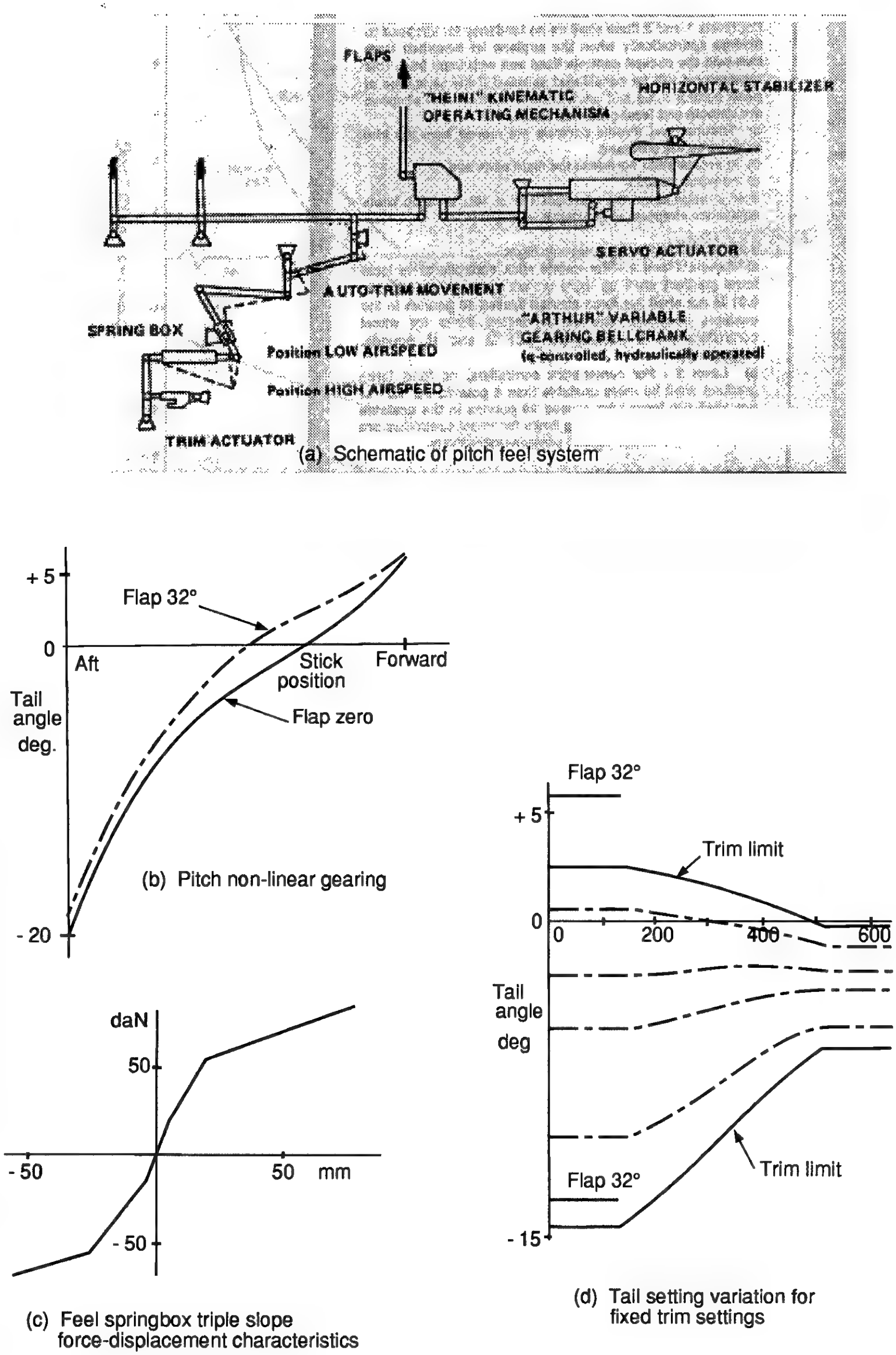
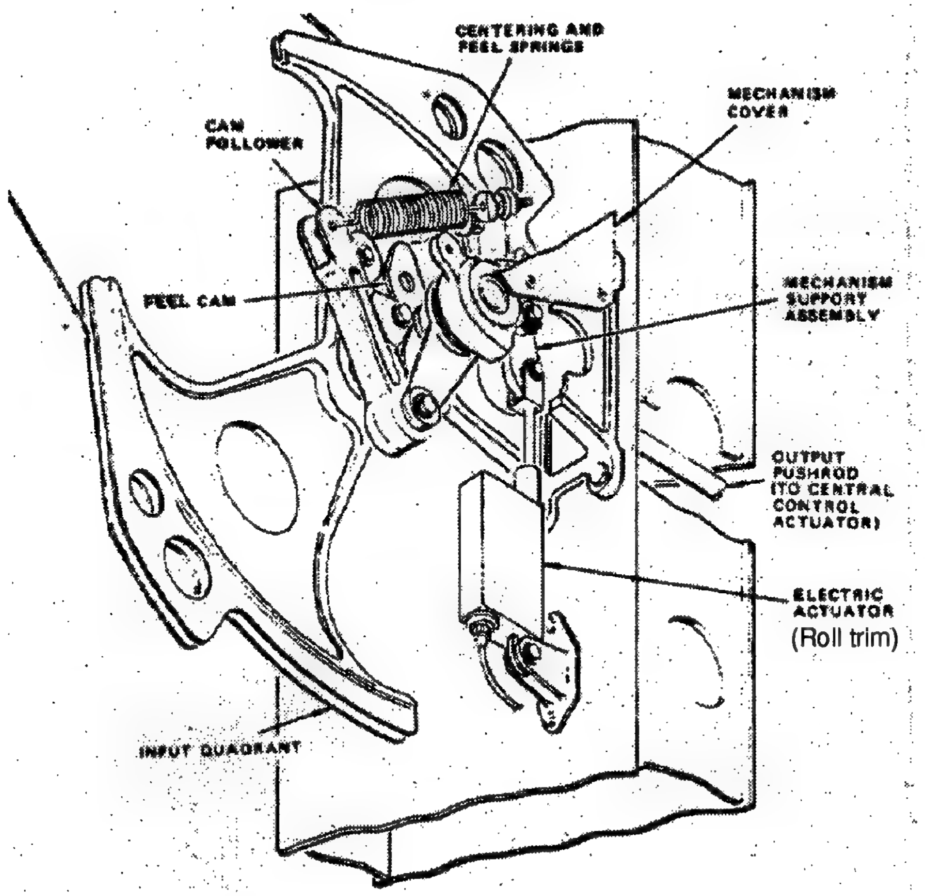
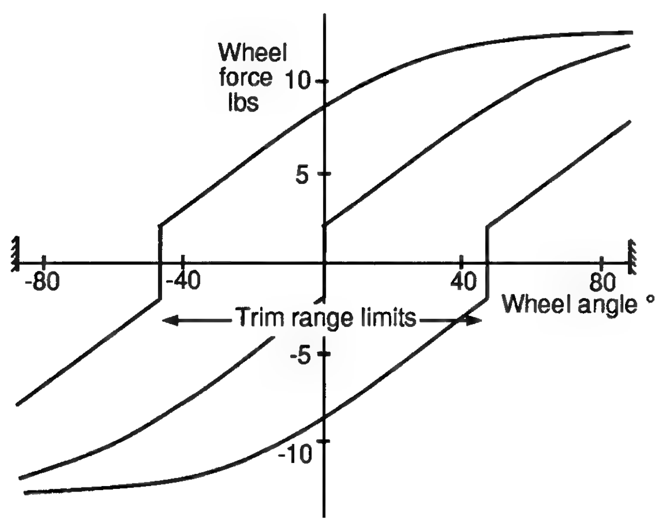


Figure 53 Dassault/Dornier Alphajet pitch feel characteristics

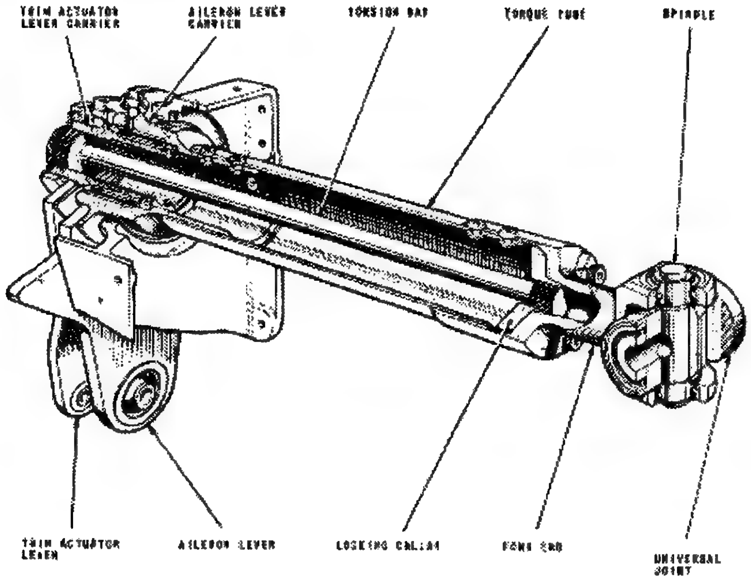


Feel unit installation

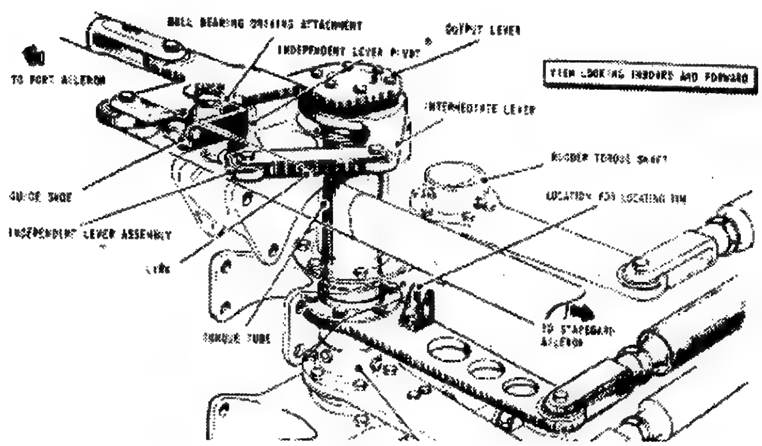


Wheel forces with/without trim

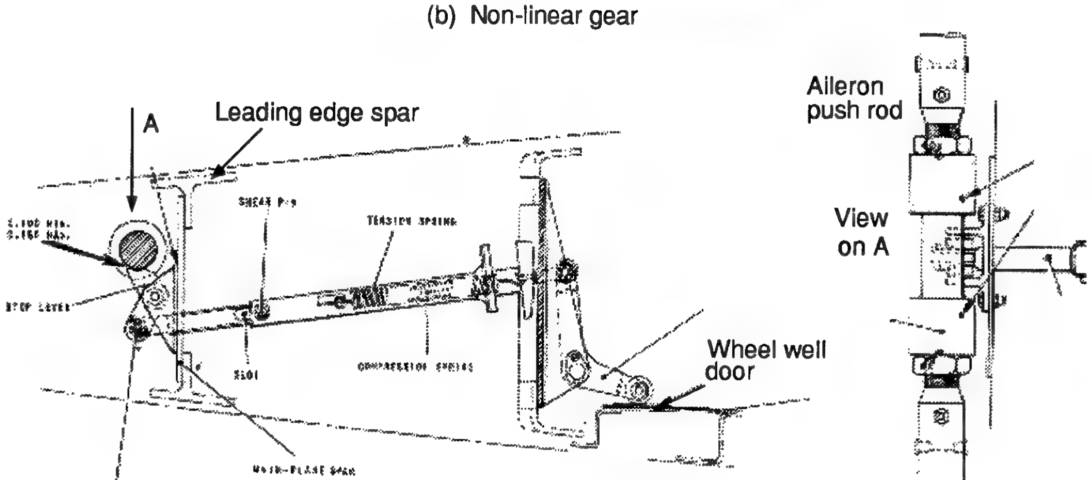
Figure 54 Boeing 747 roll feel unit and wheel forces



(a) Torsion bar spring feel



(b) Non-linear gear



(c) Travel limit stop

Figure 55 Lightning roll feel devices

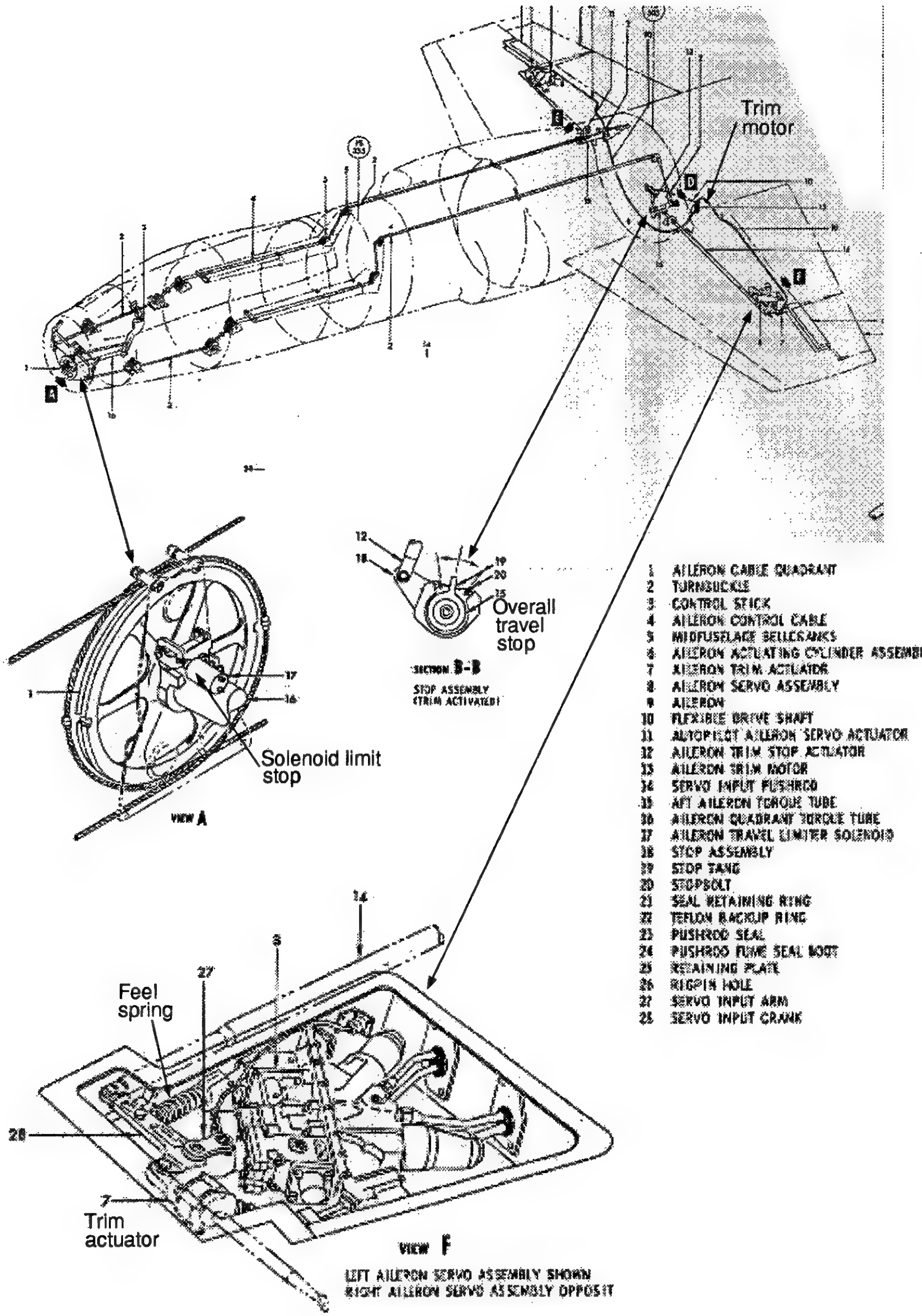


Figure 56 F-104 roll feel system

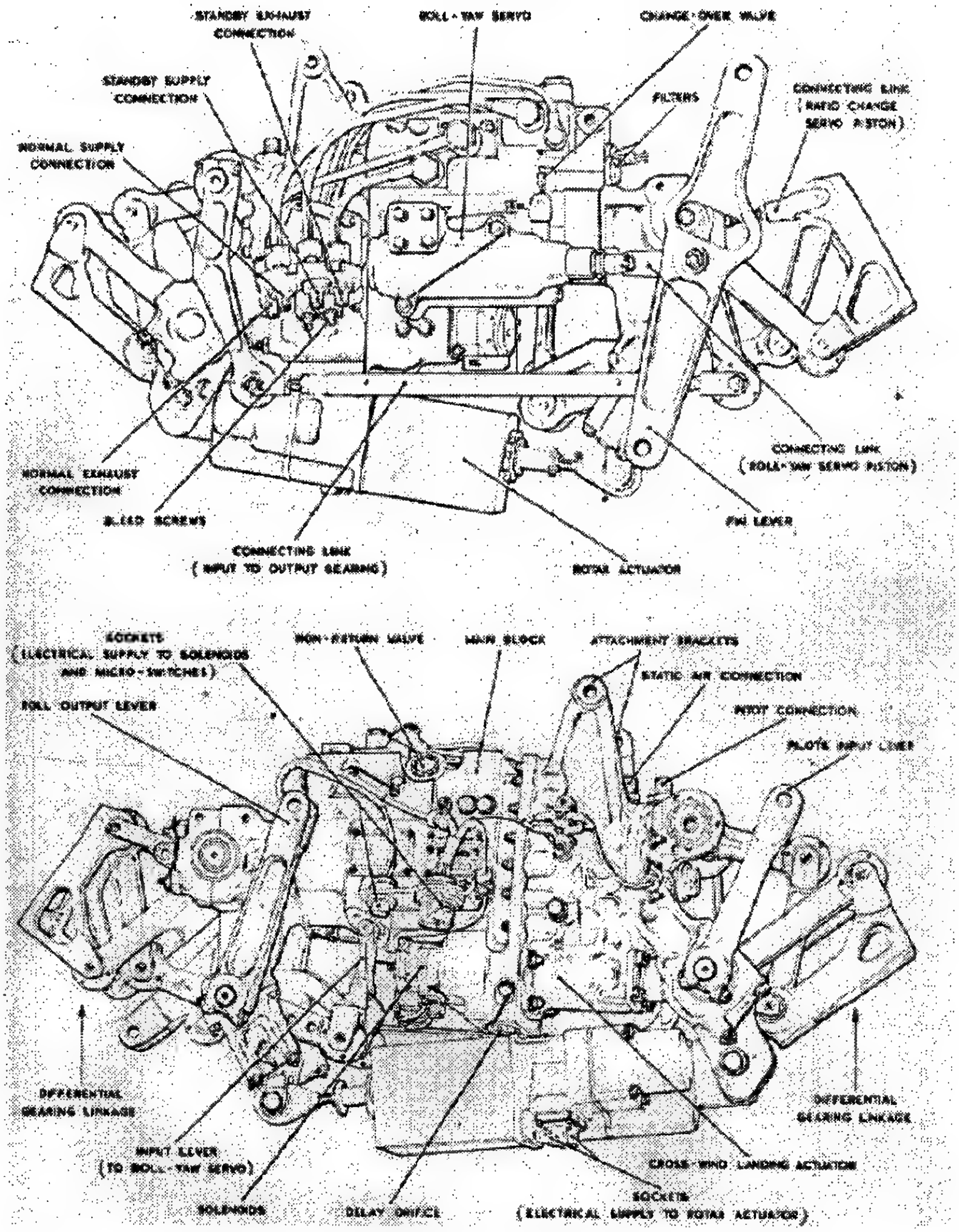


Figure 57 BAC TSR-2 variable roll authority and roll-yaw gearing

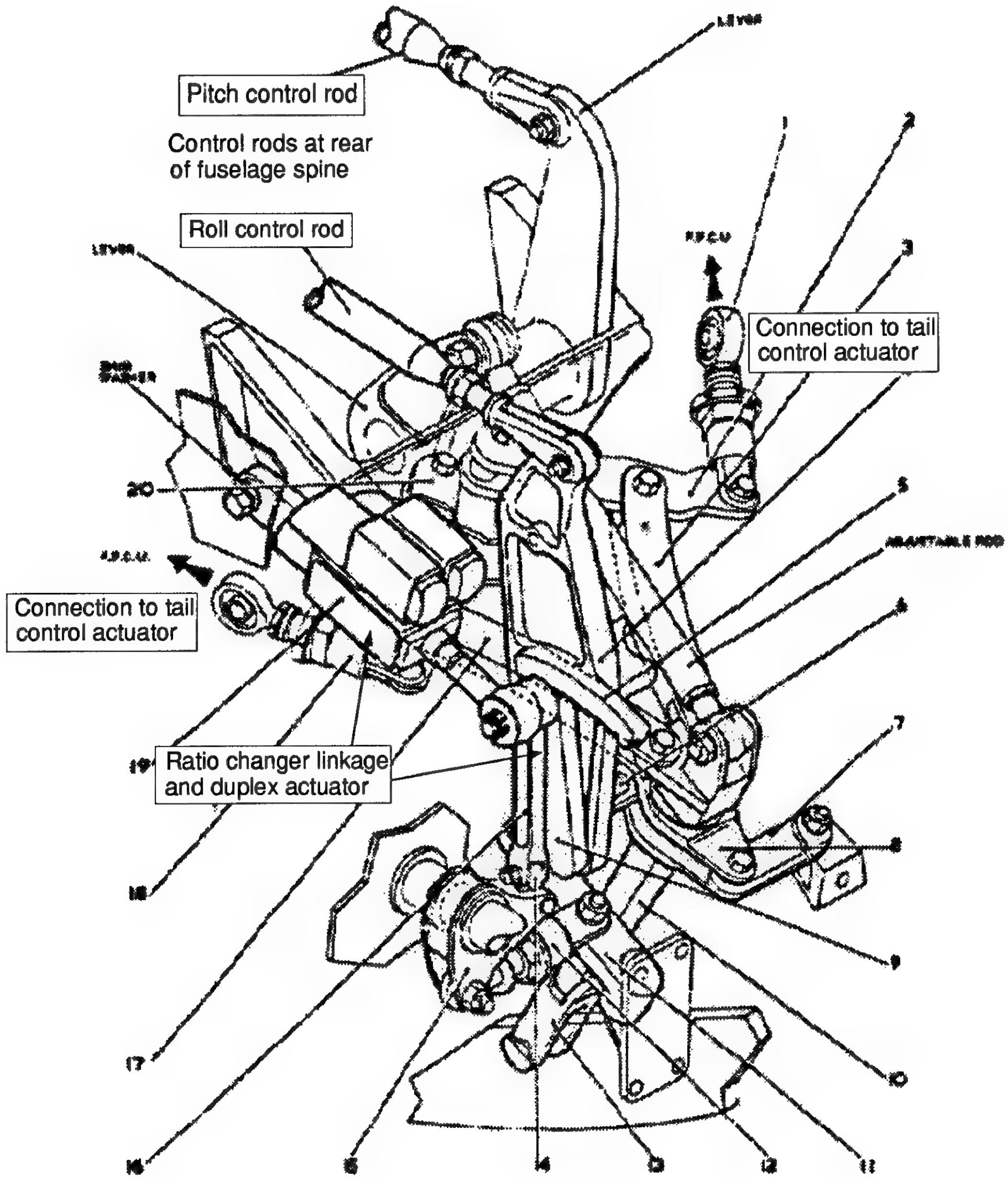
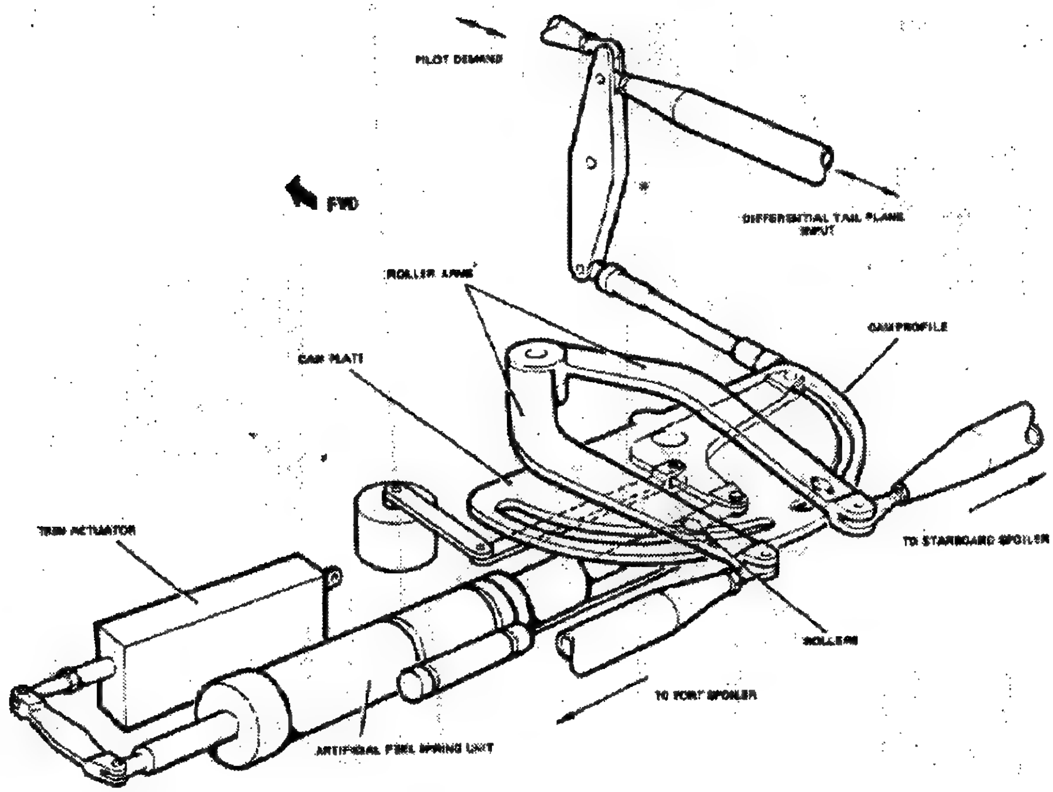
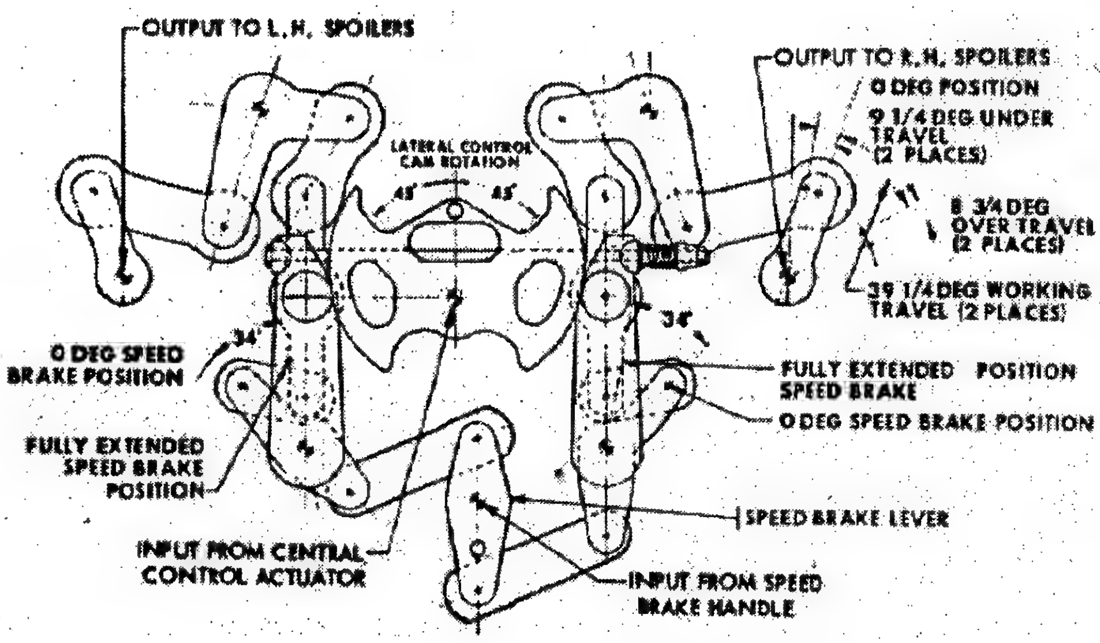


Figure 58 Sepecat Jaguar differential tail variable gearing

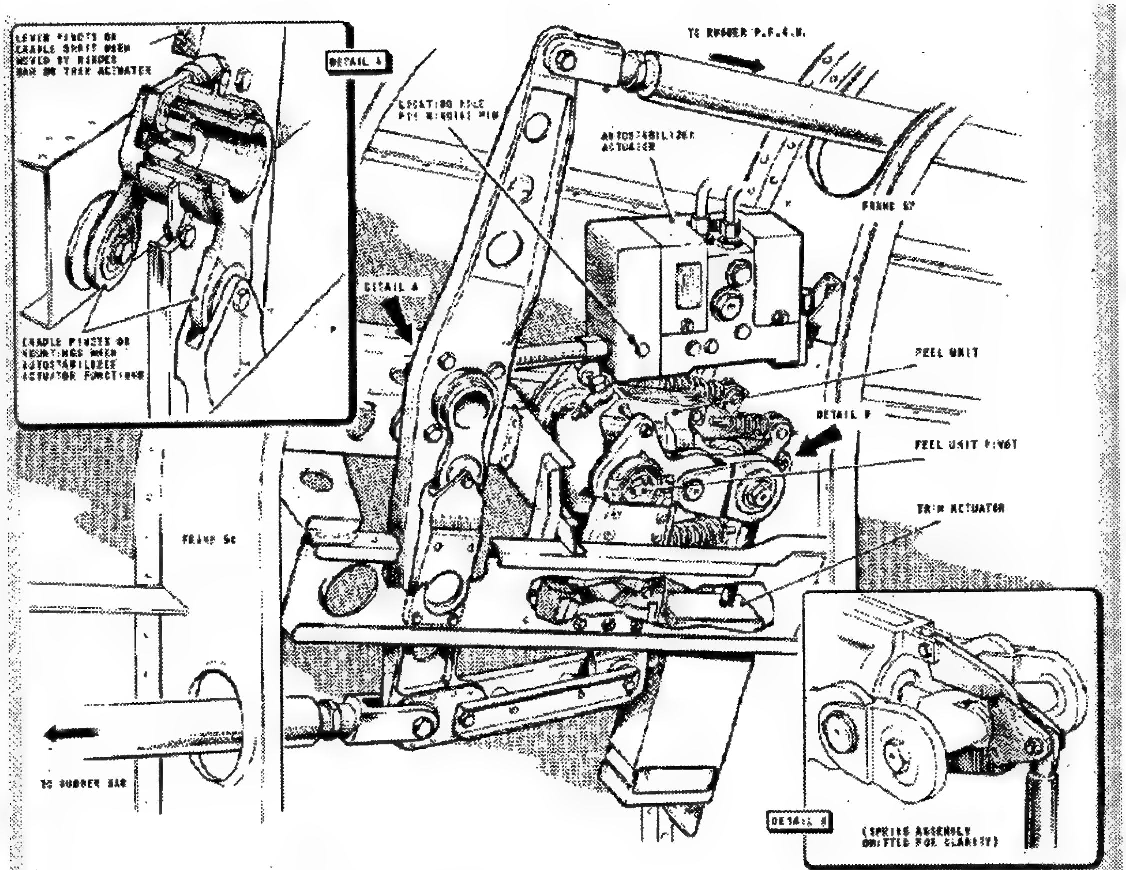


(a) Sepecat Jaguar spoiler "crab" mechanism

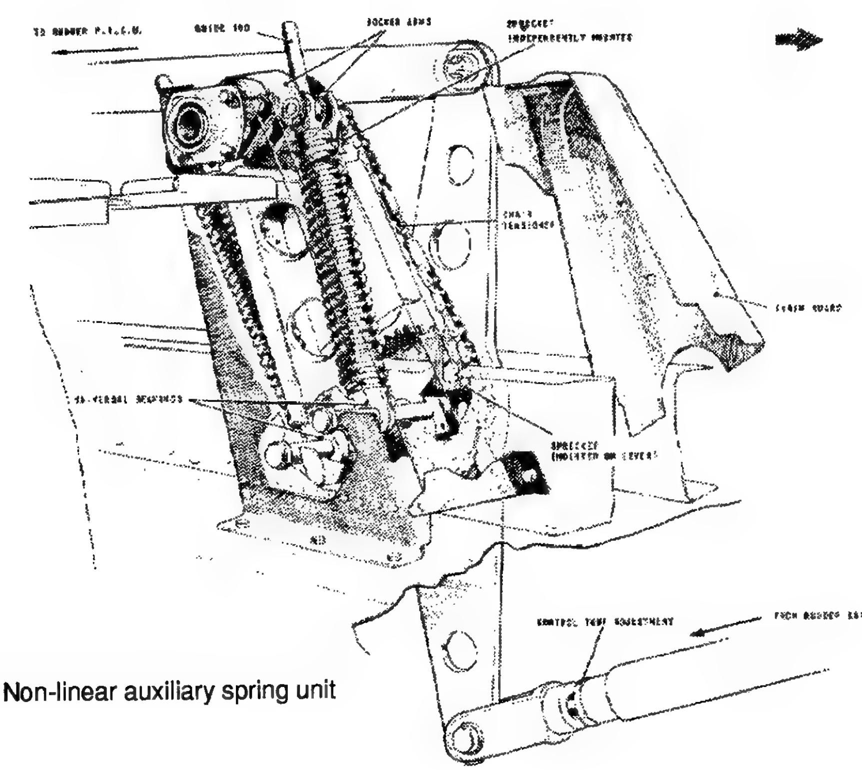


(b) Boeing 747 spoiler programmer unit

Figure 59 Non-linear spoiler gearing devices

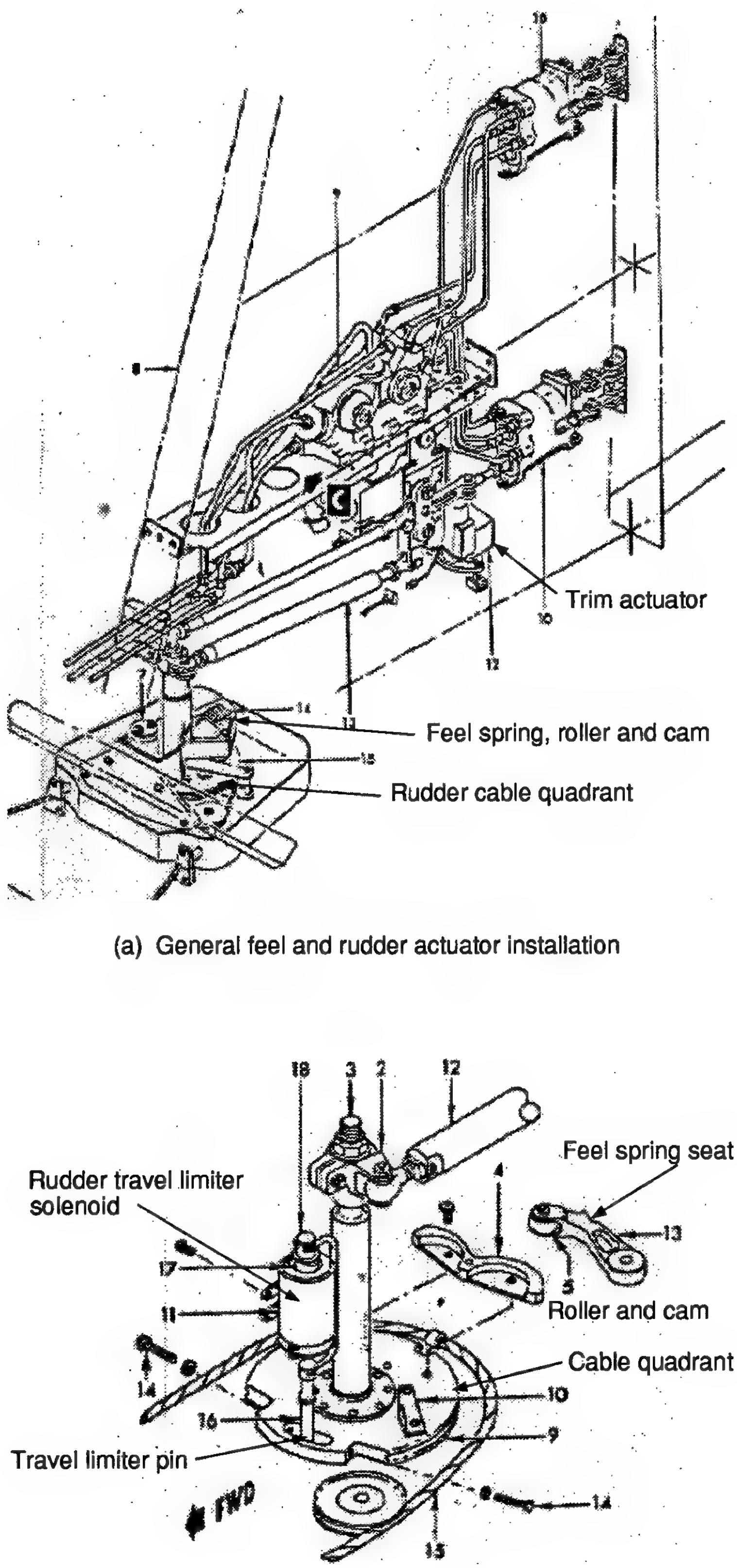


(a) Q-feel and spring unit



(b) Non-linear auxiliary spring unit

Figure 60 Lightning rudder feel unit system



(a) General feel and rudder actuator installation

(b) Details of feel and travel limiter devices

Figure 61 F-104 rudder feel and travel limiter

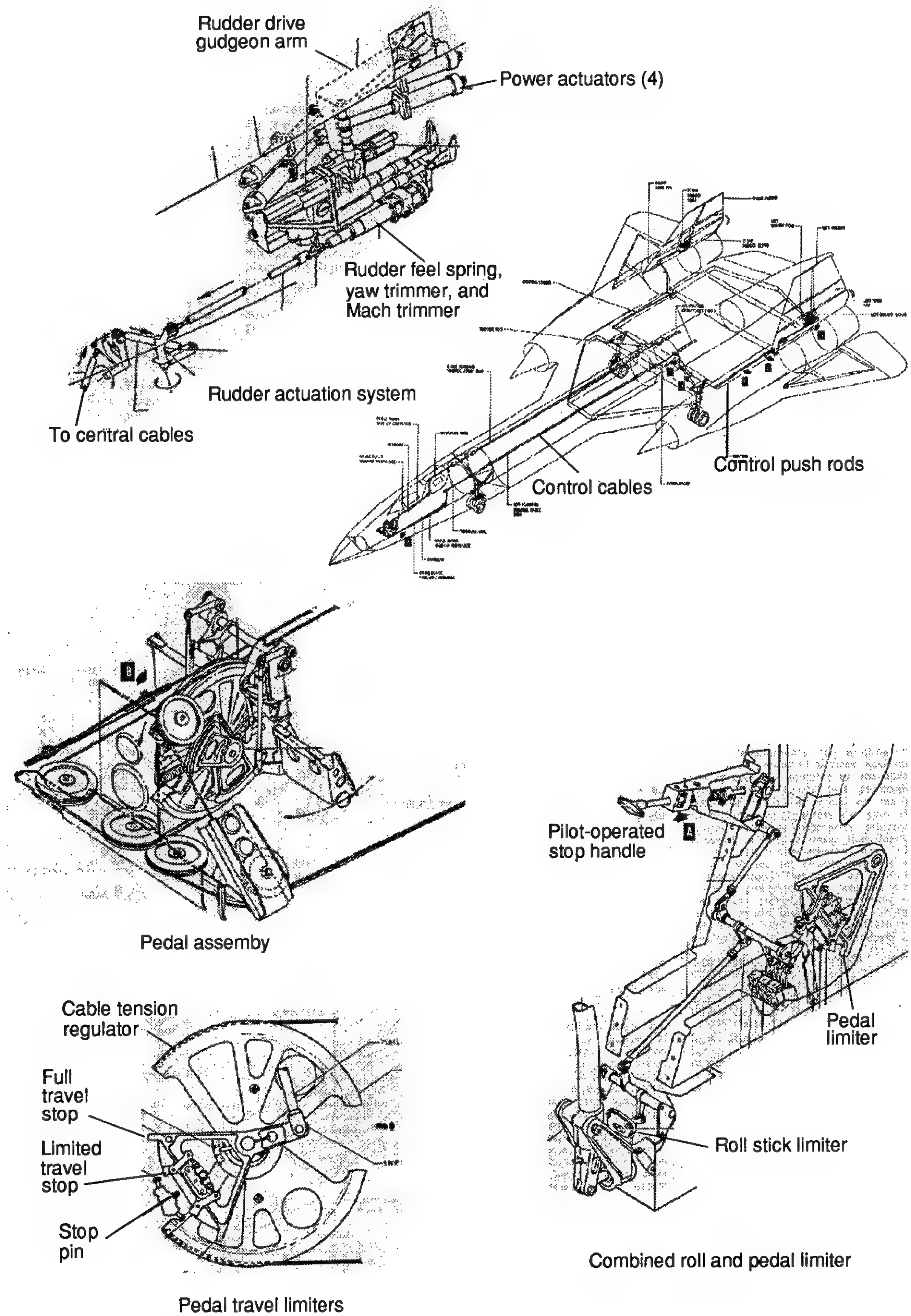
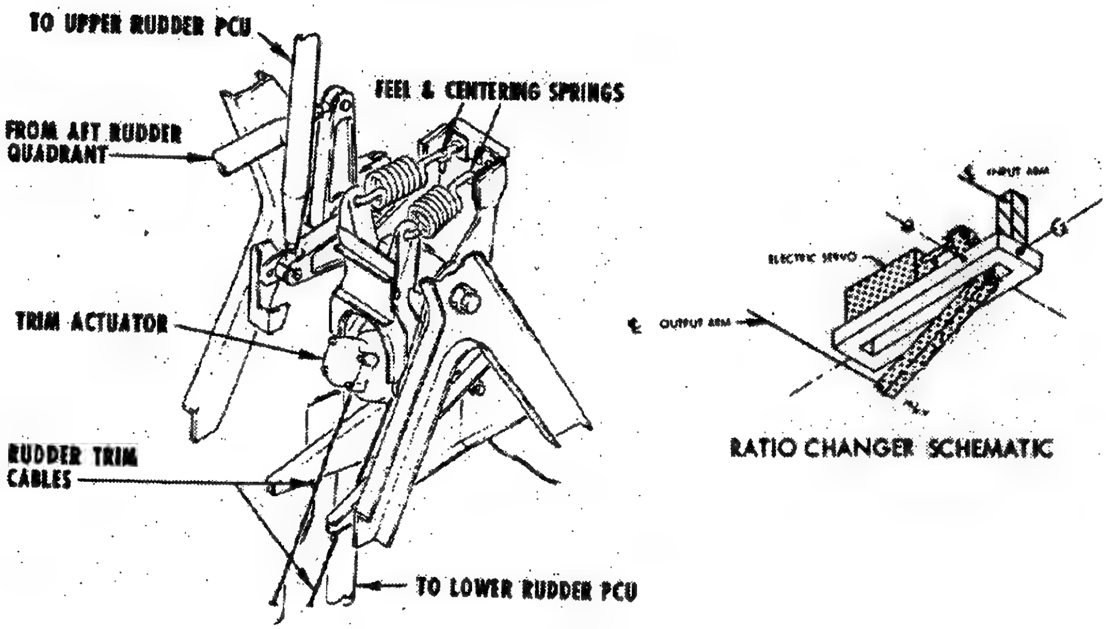
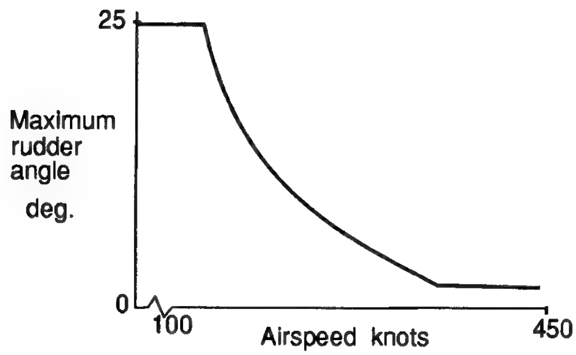


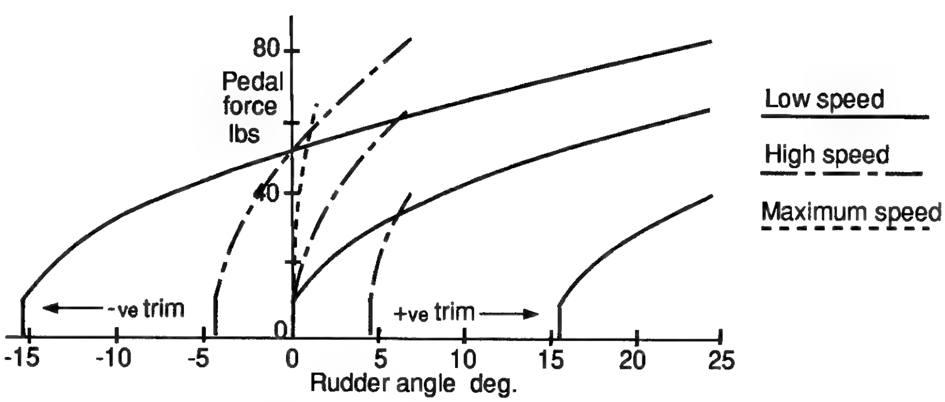
Figure 62 Lockheed SR-71 rudder control and feel system



(a) Rudder spring feel and ratio changer

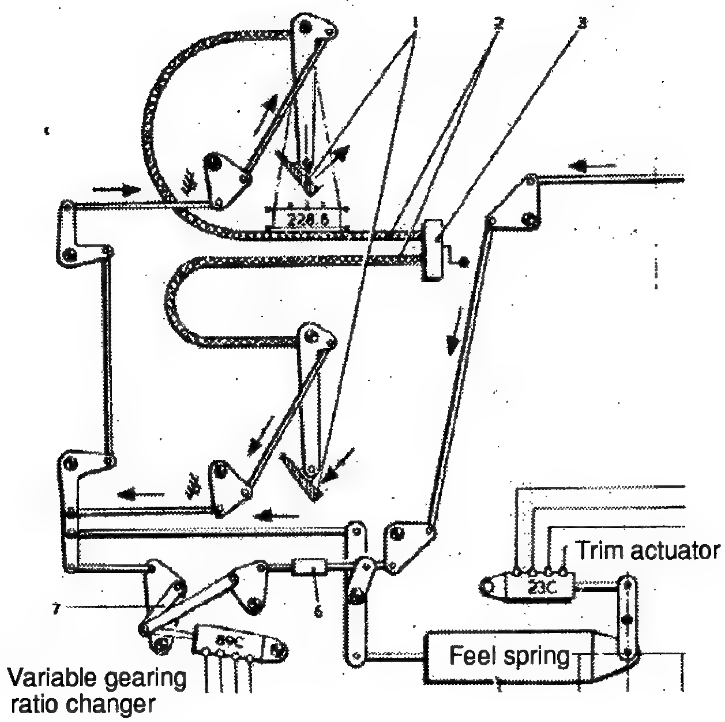


(b) Maximum rudder travel

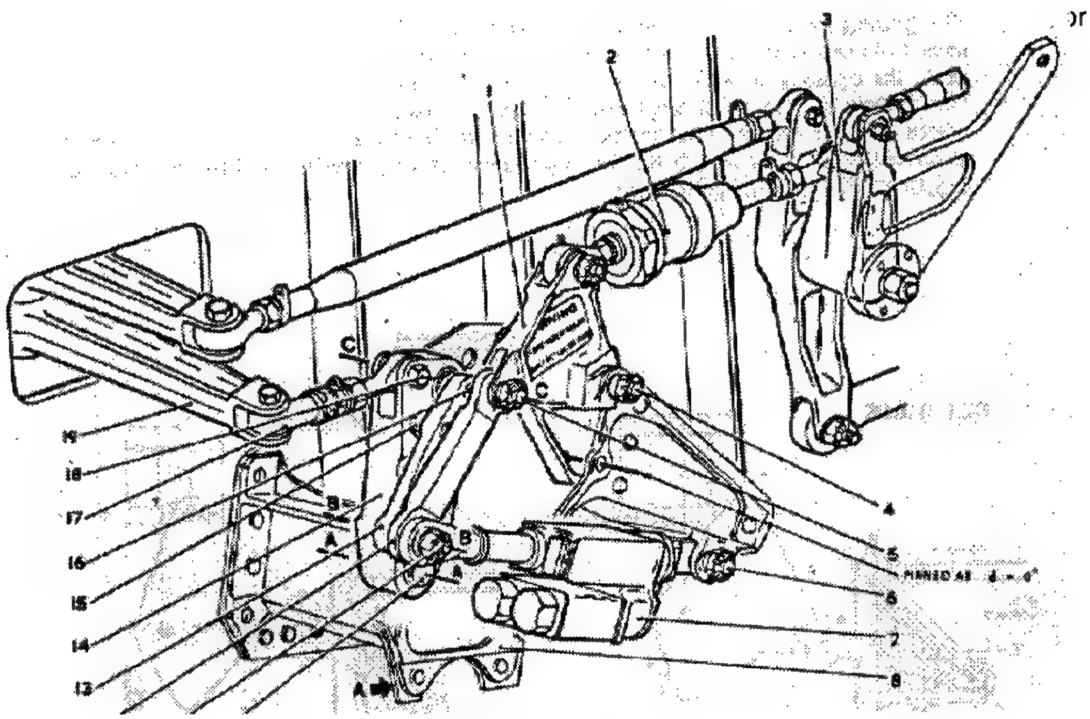


(c) Directional feel forces with/without trim

Figure 63 Boeing 747 rudder feel characteristics



(a) Schematic layout of rudder control



(b) Two-position ratio changer

Figure 64 Sepecat Jaguar rudder ratio changer

5.0 STICKS AND RUDDER PEDALS

Having been familiar devices for some 90 years, their basic design scarcely needs elaboration. The description by Loening of the stick as a "post" (§1.1) captures its essential simplicity, while a rudder bar is basically just that - a bar. This early simplicity has been largely lost, as the variations illustrated in earlier sections show, for reasons to do with improved mechanical qualities, cockpit ergonomics, pedal position adjustment, and so on. The smaller sticks used in most current fly by wire types contain much complexity in miniature in their multiplex sensors, and usually incorporate the feel devices within the single unit. Even the apparently simple "post" in the F-16 contains complex sensing devices.

Since pilots come in a standard size range, and cockpits are designed around them, it may seem surprising that standard stick and pedal designs have not been widely available commercially. If that were possible it would eliminate a significant design and development overhead, but there always seems to be a good reason for new designs. Coombs (1990) illustrates a large number of cockpits and controls, but points out that there have been more than 2000 aircraft types since 1903. Very few have been sufficiently alike in detailed cockpit design to enable standard controls to be adopted.

5.1 Conventional aircraft

5.1.1 Sticks

Even in a single manufacturer's design series, external influences can lead to the necessity for new controls, as in the Boeing 757 and 767, Figure 65. The wheel pivot centre had to be lowered from previous practice to maintain a clear view of the new electronic instrument displays. A new FAA requirement to cater for male and female pilots between five-foot-two-inch and six-foot-two-inch high resulted in an increased maximum seat height, and the wheel travel had to be reduced from ±90° to ± 65° to stay clear of the pilot's legs.

In contrast to the relatively spacious environment of an airliner cockpit, Figure 66 shows the more confined space typical of combat aircraft (Sepecat Jaguar). The width between side consoles may be quite limited, and further space is commonly taken by a centre console from the floor to the instrument panel in front of the stick. The 250 to 300 mm total pitch travel of sticks typical of this traditional design, from three decades ago but familiar for much longer before, combined with necessarily limited space between the pilot and instruments, could result in the stick grip at full aft travel making contact with the harness of bulkier pilots. (The F-104 solution to this was mentioned in §4.1.1.) Even where it did not, the geometry often resulted in a significant restriction of simultaneous full pitch and roll commands. This was usually accepted reluctantly as inevitable, but the rolling manoeuvre limitations of many such aircraft meant that this was often not too serious.

The "broken stick" design in Figure 66 with its shorter roll control element allows a typical lateral travel of ±80 to 90 mm to be used with more leg clearance than with a straight stick. The Lightning stick with coincident pitch and roll pivots, Figures 25 and 55, was installed on a floor with considerable upwards slope to raise the pedals for increased pilot g-tolerance, alleviating the lateral restrictions to some extent. It had a larger maximum lateral travel with the undercarriage down, ±5 inches (±125 mm). Full aft stick was necessary only to raise the nose for take-off. With a landing speed of about 1.5 Vs because of ground attitude restrictions, much less aft stick was needed for the landing flare so that full lateral stick was less impeded. The limited stick travel of about ±3 inches (±75 mm) with wheels up permitted generally unrestricted use, though there was always an awareness of potential conflict with bulkier pilots.

The datum assumed here for stick travel measurements is the grip reference point, or GRP, defined variously but quite similarly as the the point immediately under the pilot's middle finger when holding the stick (BAe), half an inch below the trigger (Lockheed F-117A), and the point under the pilot's second finger (Military Standard MS33574, 1969). This old U.S. standard set out the required positions of the basic stick, pedal and throttle datums relative to the standard seat datum, and their allowable movements from the datums. The stick reference point is allowed a 5 inch forward, 7 inch aft, and ±7 inch lateral travel (127, 178, and ±178 mm respectively). The pedals must have a minimum datum adjustment of 4 inches forward and 5 inches aft, a travel of ±3·25 inches being indicated (102, 127, and ±83 mm respectively). These stick travels are unduly large for modern practice with powered controls, though the full lateral allowance was certainly used in the past, e.g. in the F-104 and SR-71. However, both types have lateral travel restrictions to about 50% for up and away flight, the F-104 stick also benefitting from the unusual motion geometry raising the grip from the typically low aft position giving better leg clearance.

The range of pilot sizes which has to be accommodated in military aircraft usually includes the 5th to 95th percentile, or even the 3rd to 97th percentile. Historically based on the male population, it is now often required to take account also of the female population. The influence of new FAA requirements in this respect was noted above in the Boeing 757/767 example. With the widely variable distribution of body component length ratios as well, it can be quite difficult to arrive at a stick layout that satisfies all pilots equally. Even the size of the hand varies sufficiently to make it less easy for some to grasp the stick grip. Some pilots may be unable to rest their arm on the knee, as many like to do, while others may almost have to turn their wrist downwards to reach the stick grip. It is perhaps surprising that some height adjustment is not normally built in to a stick, accommodating the range of vertical seat adjustment which is necessary to maintain the pilot's eye position at the intended level for optimum vision.

The influence of the cockpit and stick layouts on pilots' ability to apply the necessary control effort is discussed briefly in MIL-STD-1797. The advent of fully powered control systems effectively removed the need to apply very large forces, and maximum values are in any case laid down. This is now seldom a serious consideration. The actual forces depend on the feel system and may vary widely from type to type. The maximum operational forces that may need to be applied in pitch are unlikely to exceed a range of about 60 to 100 lbs pull, but will often be far less than that. In roll, the maximum stick forces are unlikely to exceed some 10 to 20 lbs, with larger values for wheel controllers. The stick construction must still comply with specified strength requirements which are unrelated to and much larger than the operational in-flight loads. This is necessary to allow for the pilot applying gross excess forces to the stops in emergency avoidance manoeuvres, or for accidental ground loads applied by maintenance personnel, for example.

Two design features that are often not considered as significant design features are the flexible boot covering the bottom of the stick to prevent loose objects from falling into the controls, and the cable loom carrying the stick grip switch wires, Figure 66. In systems designed to low levels of friction, they may in fact be quite significant. It was completely unexpected to find in early rig testing of the Tornado controls that the stick boot added an undesirable quantity of friction hysteresis, and a change in material specification was necessary to remove this effect. The cable loom may contain a surprisingly large number of wires, requiring very careful routing past the stick pivots to prevent the creation of further friction effects caused both by high bending stiffness and by sliding action. Splitting the loom into a number of smaller looms as shown in the figure may be desirable for this reason alone. These factors are more significant when close attention is given to friction reduction elsewhere.

5.1.2 Pedals

The leg tunnels in Figure 66 constrain the pedal travel to a linear fore-and aft motion. A quite complex design may be necessary to provide both the required travel and the adjustment of the neutral positions required to accommodate a wide range of pilot leg lengths. In this example these travels are ±82.5 mm and 228 mm respectively, provided by the design in Figure 67. It will be noted that the adjustment is considerably larger than the basic pedal operating travel. As the pedal hanger lever swings through a total of about 80° from one extreme to the other, there is a variation in the effective pedal line of action and resulting pedal force and gearing. Although noticeable, it is kept within acceptable bounds because of the available length of the pedal hanger. The pedals drive the nosewheel steering with a maximum wheel angle of ±55°. Used full time under heavy braking from high speed after touchdown, the well known steering instability in this condition is alleviated by a strongly non-linear gearing, with no fine/coarse selection.

The Lightning rudder pedals shown in Figure 25 use the same principle but with horizontally disposed pedal support levers. Because these levers were constrained in length by the console spacing, and the operating travel was larger at ±95 mm, the adjustment range was more limited. As a result, some long-legged pilots were unable to operate the aircraft. The pedals are an example of the commercially available Fairey design that was once widely used in the U.K., though here the plunger locking of the spring-retracted adjustment was a modification from the standard star wheel screw mechanism.

When the two-seat Lightning was developed, with side-by-side seats, the space was too narrow to accommodate the normal pedals. New pedals carried on a sliding carriage were designed, the adjustment of such a type being limited only by the fore-and-aft space available. This design was carried on for the TSR-2, shown in Figure 68. It will be noted that the pedals operate on a tilted axis relative to the horizontal floor, raising the pedals as they are adjusted aft to correspond in part to the presumed raising of the seat pan for shorter pilots. Hence it is possible to adjust pedals in two directions to a limited extent.

The traditional pedal design features travels of typically ± 3 to ± 4 inches. The maximum forces expected with q feel are a function of the stressing design cases, for example the old U.K. 150 lbs input-and-hold and the 100 lb fishtail cases, though these would not generally require full pedal travel. For spring feel they could be characterised generally as having a 10 to 15 lbs breakout and a maximum force of 80 to 120 lbs at full travel. Constructional design strength requirements are again much higher, though perhaps not as large as the maximum two-pedal push force of 400 lbs which one pilot was able to generate in a rig test.

5.2 Fly by wire controls

5.2.1 Sticks

Some early fly by wire types used conventional sticks with a separate feel system, and indeed some retained a conventional mechanical control back-up system. Now that such back-up is no longer common, the pilots' controls may be considered as a separate class because they carry within a single unit the complete artificial feel and a precision command sensor package. The Boeing 777 is a notable exception, having maintained a traditional "look and feel" as a deliberate policy. Many fly by wire research project aircraft also retained a standard layout but with no such back-up, e.g. the Jaguar FBW and X-29 (though this was subsequently modified). The SFCS FBW YF-4E was fitted with both a centre stick and a sidestick (Ramage). Its mechanical back-up system was removed after finding a degradation in small amplitude stability arising in the change-over mechanism. In-flight studies of "electric sticks" began no later than the early 1950's, and included rigid centre sticks and side sticks with and without motion (see the list of further reading matter). While the research was primarily aimed at studies of fly by wire control laws, much was learned about stick characteristics along the way.

Newell (1954) and Russell (1959) found that a rigid centre stick could be used, but it had no advantages over a conventional displacement stick. Russell found that roll control in particular was unsatisfactory due to lack of friction and inadvertent inputs, due for example to gripping the stick, with roll accelerations some 20 times greater than in pitch. Pilots thought that some motion was desirable. Although it would be possible to alleviate such problems to an extent by careful shaping of the stick output signals, nobody has subsequently considered there to any valid reason for pursuing an unprofitable course to an undoubtedly inferior rigid centre stick in a production aircraft. It has been known for avionics engineers to ask for a rigid centre stick to gain unobscured panel display space, but it is scarcely necessary to point out that the area visually blanked by lateral stick movement is of no interest to the pilot at the time.

Figure 69 shows the Lockheed F-117A floor mounted centre stick, of conventional overall dimensions but with reduced travels. In pitch the travel of the GRP is about 4·1 inches (104 mm) aft and 2·1 inches (53 mm) forward, on a 20·3 inch (516 mm) radius. The spring gradient is about 7·0 lb/inch (1·23 N/mm) giving corresponding stick forces of 29 lbs (129 N) pull and 15 lbs (66 N) push. In roll the travel is ±2·6 inches (±66 mm) on a 19·8 inch (503 mm) radius, with a spring gradient of about 4.6 lb/inch (0·8 N/mm). The roll pivot was offset to achieve a slight lateral non-linearity giving maximum forces of 12·5 lbs (55 N) to the left and about 11·5 lbs (51 N) to the right, allowing for the greater ease of applying forces to the left (see §6.1). Three identical spring/damper cartridges are used to provide the feel forces, two for pitch and one for roll.

Figure 70 illustrates two of a family of fly by wire sticks made by GEC-Marconi Avionics Ltd., in this case the sidestick for the Lockheed YF-22A and the centre stick for the BAe EAP demonstrator aircraft. Others in this family include generally similar centre sticks for the Eurofighter 2000, McDonnell Douglas/ General Dynamics A-12 ATA, and DRA VAAC experimental fly by wire Harrier, and the sidestick for the F-22A. Further details of the EAP stick are given in Figure 71. Separate spring and damper packs are used, each readily modified to provide a wide range of stiffness and damping as required for different applications. Overall this stick was considered a great improvement over previous more traditional types, with excellent damping and centring, and with good clearance from the harness and seat pan ejection handle even with a 99 percentile pilot. Initially the cable loom friction caused an irritating degradation of the small displacement qualities, but this was resolved by development.

The force and displacement characteristics of the EAP stick are broadly representative of some other fly by wire combat types, e.g. the Dassault Mirage 2000, the IAI Lavi, and the Eurofighter 2000. The pitch travel has two aft stops, the soft one defining the standard demand range which prevents exceedance of normal acceleration or angle of attack limits. By pulling through to the hard stop, these limits can be exceeded. In the Mirage 2000, 10 g in the A/A mode or 7 g in the A/G mode can be pulled in an emergency. Experience in the EAP suggested that the 205 N soft stop over-ride could be inadvertently passed too easily even single-handed, and it was recommended that a good two-handed pull should be necessary. It was stiffened up substantially in the Eurofighter 2000.

A major difference from tradition in most of them is the absence of trim displacements, an exception being the I.A.I. Lavi with a mechanical feel trim in pitch. Conventional trim switches are used, but they act as series or datum trimmers signalling the control laws and not the feel spring positions. The reduced stick

travels available reflect this effect more than a change to normal manoeuvring gradients. The actual pitch feel gradients remain similar to many conventional aircraft. It is noteworthy that the F-117A stick travels are quite similar, though with even smaller rotation due to the longer stick, despite the entirely different aircraft roles.

In the EAP, because of the shorter stick the angular pitch travels are much the same as in traditional sticks. At ±15° lateral deflection, the angular rotation demanded of the pilot's wrists is much reduced from the traditional "broken stick", e.g. ±36° in the Jaguar, ±24° in the Tornado, and even ±40° in the early Blackburn Buccaneer (later found to be excessive for low speed handling and it was reduced to ±25°). This is especially an advantage in the full aft-full right position which can demand an awkward wrist articulation. Two further recommendations that resulted from this experience were to reduce the maximum right hand force to 80 or 90% of the left hand maximum, and that reshaping the stick grip top would alleviate any remaining aft-right difficulty.

In a conventional aircraft, a small trim error only results in a small change in the steady state trim. In a fly by wire system with forward path integrators, good mechanical centring is necessary to prevent an extremely irritating drift away from the desired trim state. Precise centring in the Lockheed and the GEC-Marconi sticks is obtained by spring preload detents just sufficient to overcome the small friction hysteresis of probably less than 1·0 lbs (4 N) overall. Since absolutely perfect centring is impossible, a small signal deadspace is still necessary to ensure a zero hands-off command. This deadspace would not lie in the displacement sensors, however, but in the control law structure. Careful attention must be paid to these aspects since small deflection deficiencies can be very obvious among otherwise high quality fly by wire characteristics.

In principle it is possible to use force sensors, even on a stick with displacement, acting against the reaction of the feel springs, but early experience in the SFCS FBW showed unsatisfactory features. Ramage noted problems with strain gauges such as sensitivity to humidity and calibration variations with time. The SFCS FBW also showed the problem found by Russell of inadvertent inputs and abrupt lateral overcontrol. After an abrupt aileron 1g entry roll in which the aircraft was inadvertently commanded to more than -4g, it was found that the stick could be "torqued" by wrist articulation to give pitch inputs in the opposite direction to the intended displacement. The poor performance, with the difficulty of matching gauges in redundant systems and of compliance with other inter-related components, led to the recommendation that strain gauges should not be used for stick sensors, and that the sensor package must detect only the applied shear forces and not torques.

To the author's knowlege, LVDT position sensors are used on all recent or current fly by wire sticks. The F/A-18 initially used force sensors, but these were as unsatisfactory as in the past experience. Attempts to filter out the oversensitivity to the pilot's inadvertent twitches and jerks, measured as control inputs by the stick force sensors in the F/A-18, caused degradation to the handling qualities, and they were replaced by LVDT position sensors. Even the original nominally rigid force stick in the F-16 used LVDT's to detect the very small flexure beam displacements within the stick.

The F-16 Lear Siegler sidestick originated in the YF-16 Light Fighter prototype as an experimental concept based on the force sensor from the A-7 Corsair II stick, and was continued into production. Although it was able to perform the functions required of a control stick, it was unsatisfactory in many respects. Some examples given by Garland were: pilots were taught not to touch the stick on take-off until lift-off speed was reached, due to cross-talk and inadvertent inputs (factors contributory to the famous YF-16 "Flight 0"); most tracking tasks resulted in pitch bobble; lack of pilot-to-pilot consistency in tracking performance; difficulty in maintaining accurate attitude on the approach in turbulence, due to pitch-roll cross-talk; wrist fatigue from applying excessive control force in full stick manoeuvres, due to lack of positive travel stops; and a roll ratchet tendency.

The introduction of the small amount of movement shown in Figure 72, together with attention to wrist and arm rests, greatly improved the characteristics. No increase in forward motion was provided, as this had been found to create problems in push-overs as the pilot's wrist floated off the rest. Although the aft stop cue was satisfactory, the lateral stops were still not thought to be sufficiently obvious. However, it was generally felt that the new stick would enable safer and easier pilot transition into the F-16 than with the fixed stick.

5.2.1.1 Large aircraft

Despite the few examples of fly by wire in large aircraft, these have used the widest possible variety of pilot's controllers. Early experiments with a B-47 sidestick were successful (Ramage), with a significant reduction in workload and pilot fatigue. The wrist action stick with very small forces provided precise control with minimum effort, though clearly this was also assisted by the stability augmentation and the absence of prolonged heavy manoeuvring tasks.

Space vehicles, though perhaps not strictly aircraft, were the focus of much research into controllers, leading ultimately to the Shuttle Orbiter, which uses the Apollo type wrist action hand controllers. These have their roll pivot just below the grip, while the pitch pivot is near the top of the palm, favouring the pulse type of input appropriate to its pitch rate command-attitude hold system with virtually only steady flight requirements. The stick is used for both normal aerodynamic flight, and for orbiting reaction control attitude system. The latter is essentially an on-off function and ideally would use a different feel characteristic, but this was optimised for aerodynamic flight and the result accepted for orbital flight. Though not absolutely ideal, the result is a simple, lightweight and acceptable controller.

The Airbus A-320, A-330 and A-340 wrist action sidesticks are a complete break with the traditionally conservative approach to airliner design (Corps). They were adopted partly because it was conceptually feasible in the absence of the usual mechanical control system, but also because it was seen as making best use of the fly by wire qualities and because it removed any compromise previously necessary in the instrument panel and cockpit layout necessary to accommodate the traditional control wheel and column. The decision was made after preliminary research in a Concorde (Cazenave/Irvoas) and further tests in an A-300 with 48 pilots confirmed the feasibility. Ultimately some 100 pilots were involved in the assessments. The sticks are mounted outboard of each pilot, with travels and forces of ±16° and ±22 lbs in pitch, ±20° in roll with asymmetric forces of 9 lbs inboard and 7 lbs outboard. There is no mechanical or other interconnection between the sticks, which can be moved independently, and they do not move to follow autopilot commands.

The Boeing 777 maintains an entirely traditional approach in its controller design, discussed in §4.1.3, following a completely opposite philosophy to the A-320. It was considered to be important to maintain the conventional cues obtained from the controllers, including variable feel, cross-reference between pilots, and autopilot cues. An interesting discovery was made in a questionnaire of pilots of the A-320 and another conventional type (Field) that about 85% rated the controllers in their own aircraft equally well, the other 15% expressing a wish for the other controller type. Almost all "conventional" pilots wanted the backfeed of the other pilot's stick position and of autopilot commands. 60% of the A-320 pilots also desired the former but only 30% the latter, though they do not have either. The controversy is well known and need not be pursued here.

Yet another choice was made for the McDonnell Douglas C-17A military transport. Because of the stringent demands on manoeuvrability associated with rough and small field performance requirements, a centre stick was chosen. This experienced some problems of aeroelastic pilot-augmented coupling of the roll ratchet type, created by front fuselage lateral oscillations following sharp roll control inputs (Norton).

5.2.2 Pedals

Only one flight experiment to examine rigid pedals is recalled by the author, though the reference is lost. This clamped the control cables at the input to the rudder actuation and measured the control input by force sensors. Unfortunately there was so much cable stretch that the pedals moved sufficiently to provide a travel gradient of 1 inch for full rudder, which proved to be acceptable. Individual force measurement on separate rigid pedals can give ambiguous signals because both feet may press simultaneously, and it also requires expensive duplication of multiplex sensors. Even for quasi-rigid pedals, therefore, the basic rudder bar mechanism is preferable from which a single force measurement is possible. As far as is known, no aircraft has used rigid pedals, and there seems to be no justification for considering their use. Several aircraft have used much smaller pedal travels than the traditional ones, one of the smallest being in the I.A.I. Lavi with ± 0·5 inches (±12·5 mm).

Figure 73 shows the F-117A rudder pedals. The travel is ±1·12 inches (±28 mm), with a spring detent breakout of ±11 lbs and a maximum force of nominally ±90 lbs (±49 and ±400 N respectively), provided by dual spring/damper cartridges. Hence the pedal forces are conventional but the travel is much smaller. This figure could almost be used to illustrate the pedals of the BAe EAP and the Eurofighter 2000 as they are very similar in concept, though the travel is slightly greater at ±1·35 inches (± 35 mm) and the forces slightly less. All-speeds nosewheel steering is used on the latter aircraft with non-linear command gearing. With the steering instability under braking eliminated by their yaw rate steering stability augmentation, the small pedal travels have caused no difficulty whatever in the landing decelerations. With the pedals virtually untouched due to the high degree of augmentation, no difficulties have been observed in any stage of flight.

5.2.3 Throttles

Little has been published concerning throttle designs. It has been universal to use a relatively large displacement, typically some 175 to 225 mm for left hand use in combat aircraft. This may be either a linear slide type or a simple pivoted lever. Airliners appear to use at least as much throttle movement. Military Specification MS33574 specifies only the same maximum forward position of the throttle as of the stick, except for catapult launched aircraft where this is 5 inches less to ensure positive control. Throttles are conventionally back-fed from the autopilot to allow transient free take-over by the pilot and to provide continuous cues about the thrust management.

An exception to this is the Airbus fly by wire series, which have significantly smaller throttle travels without back-feed from the autopilot. While these have some well liked features of power condition selection not found conventionally, the Field questionnaire found 71% of its pilots would like such back-feed to restore a full energy and situational awareness.

The issue of rigid throttles has been raised in the past (though probably only by avionics specialists). The way in which pilots use the throttles appears to preclude such an idea completely, and no practical example is known. The positional cue from the throttle position gives the pilot instant command of large thrust changes, which generally will not be achieved until some time later. Small movements can be easily made for fine adjustment, observing instrument readings of actual thrust. Without throttle displacement, further instrumentation of demanded thrust would be necessary. The pilot would not be able immediately to divert activity to other necessary areas until the force output had generated the demanded level, a process that clearly cannot be performed as rapidly as physical throttle movement without making both fine and coarse thrust selection rather difficult and imprecise.

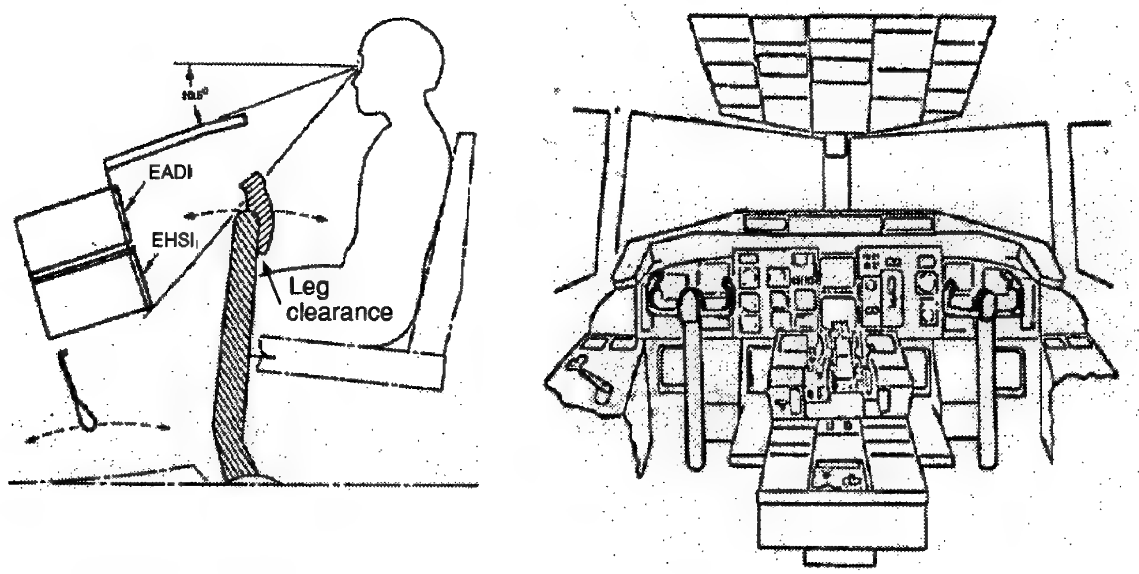


Figure 65 Boeing 757/767 control wheel constraints and cockpit environment

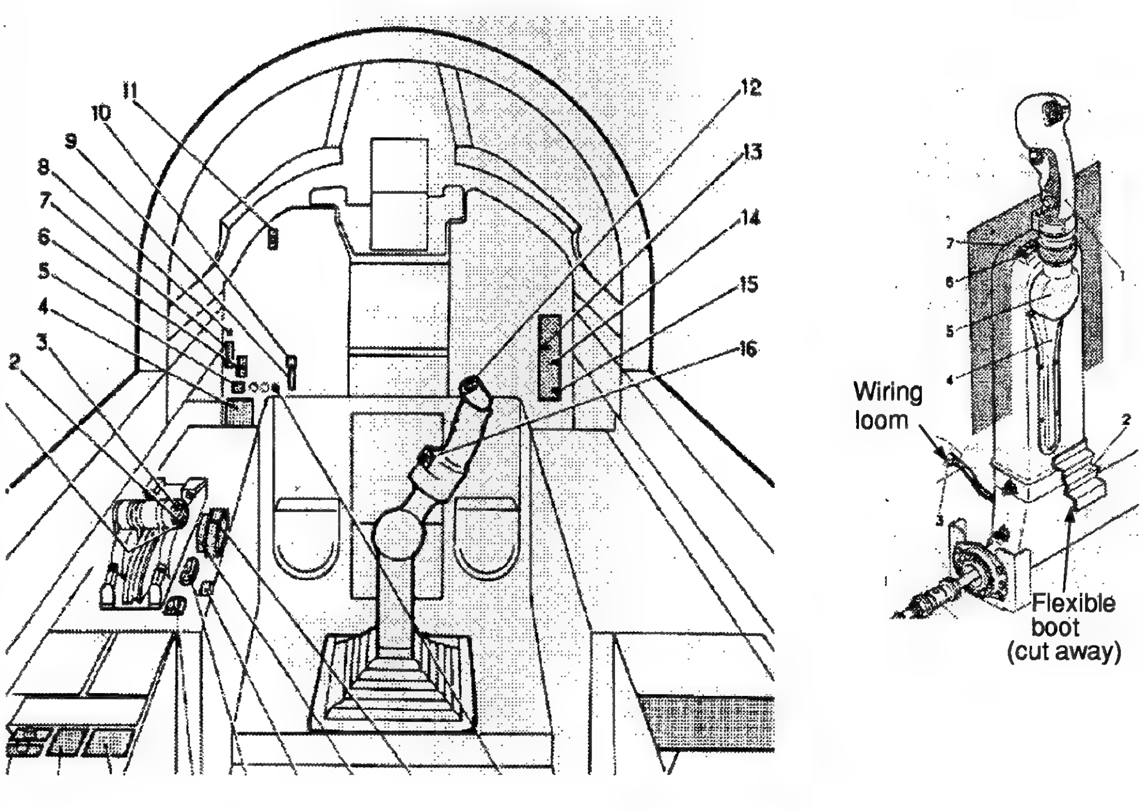


Figure 66 Typical combat aircraft cockpit controls environment

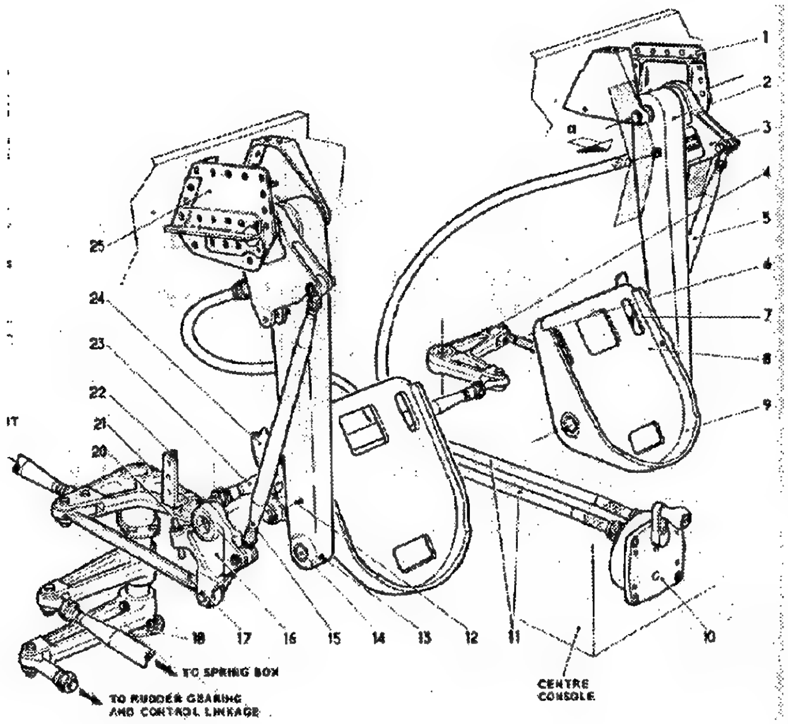


Figure 67 Rudder pedals - pendular type

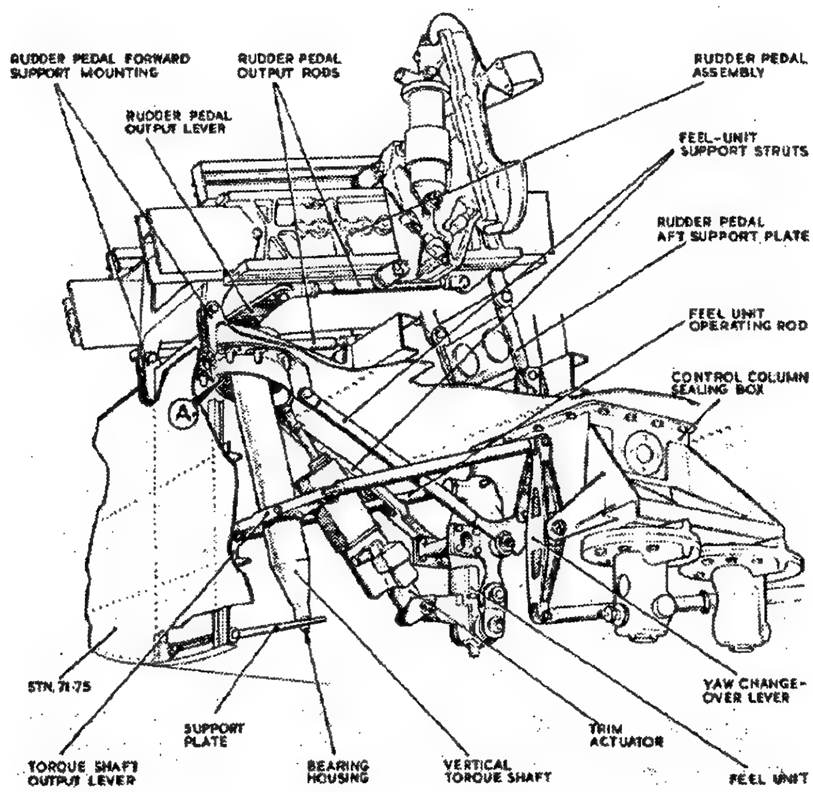


Figure 68 Rudder pedals - sliding carriage type

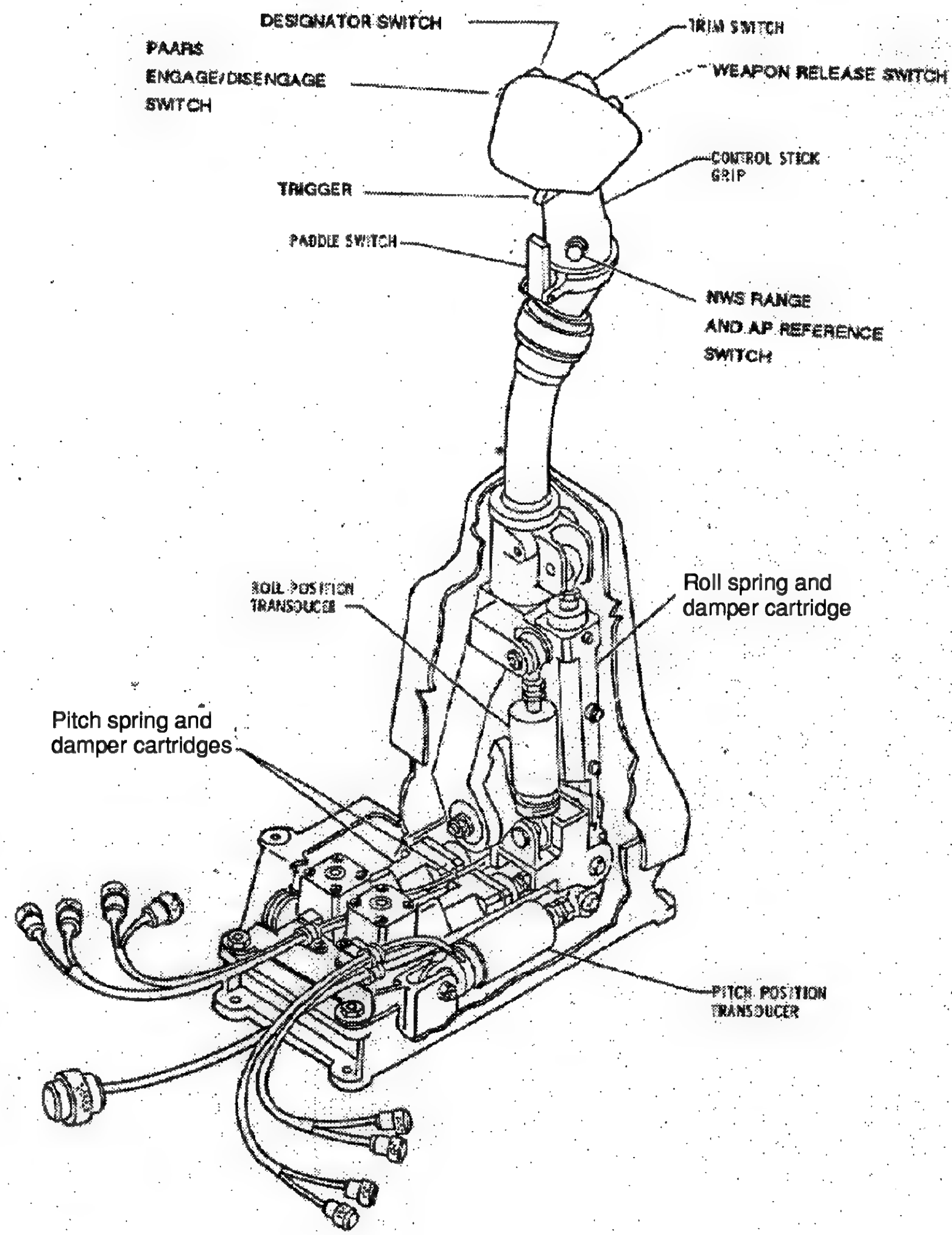
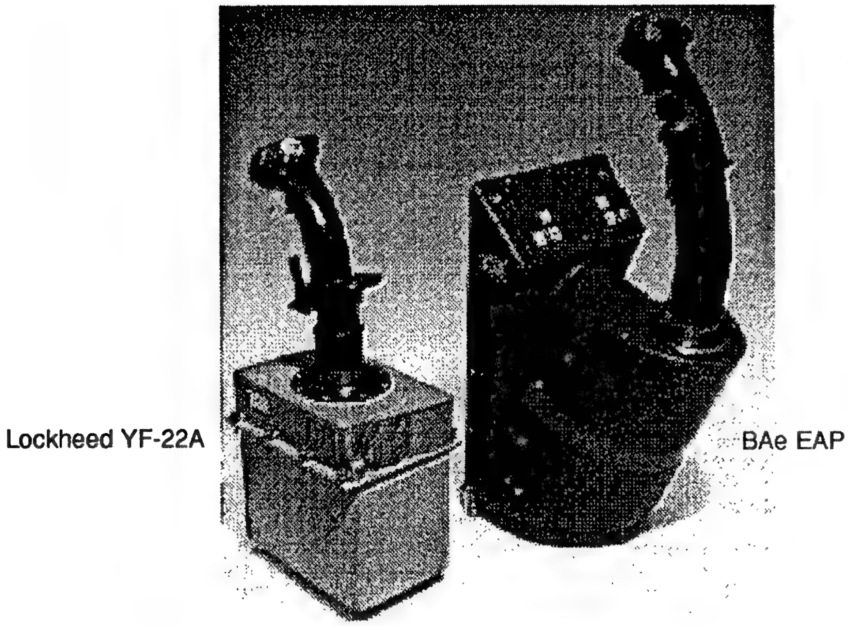
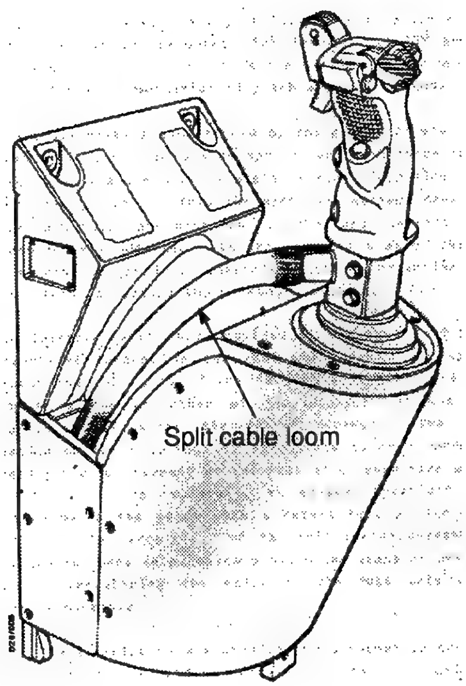


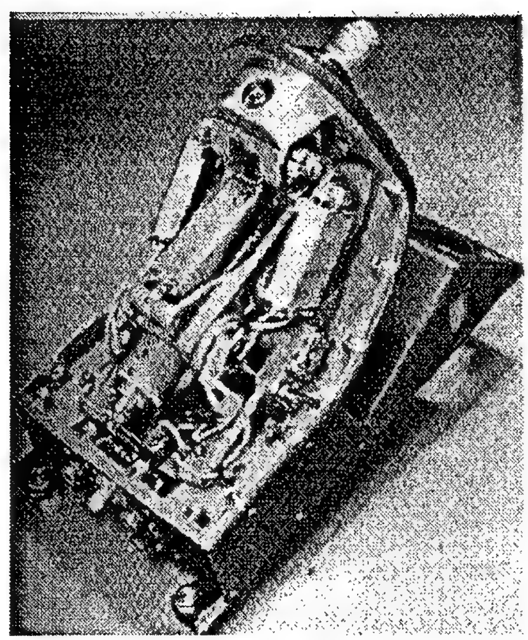
Figure 69 Lockheed F-117A control column, feel and transducers



Fly by wire side and centre sticks

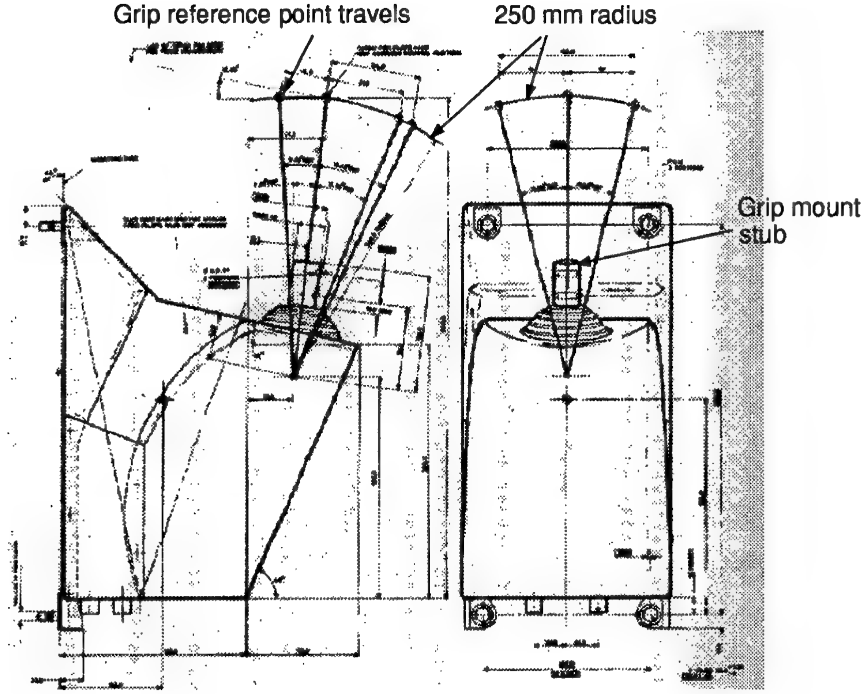


EAP centre stick assembly

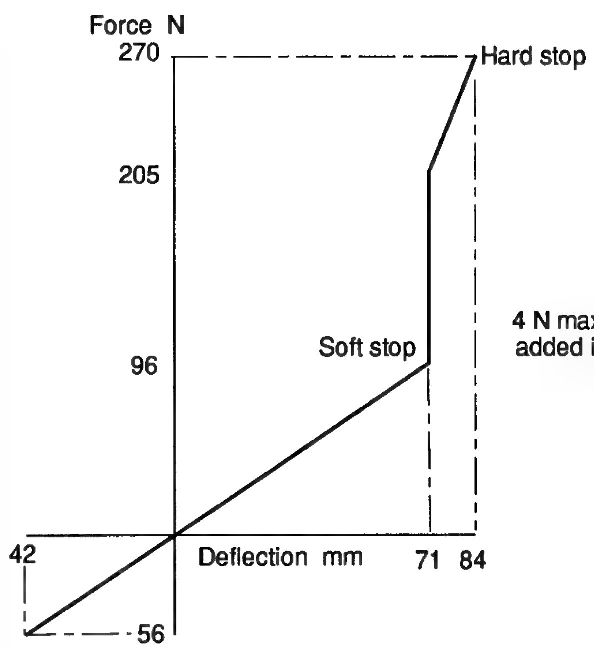


Internal mechanism of EAP stick unit

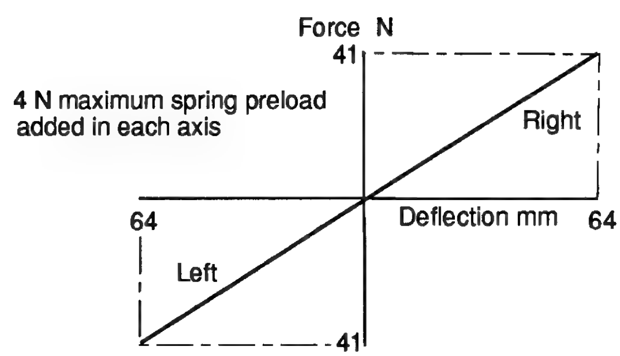
Figure 70 GEC-Marconi Avionics fly by wire control stick assemblies



EAP stick assemby schematic



Nominal pitch stick forces



Nominal roll stick forces

Figure 71 BAe EAP control stick forces and deflections

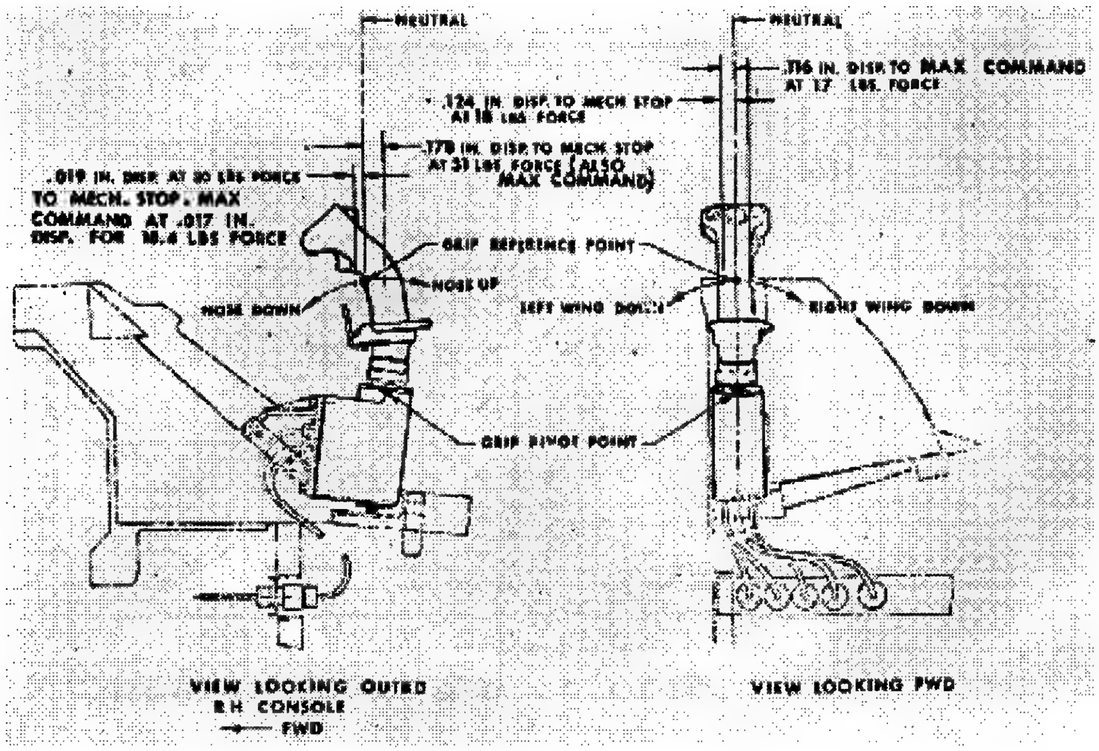


Figure 72 F-16 minimum displacement sidestick

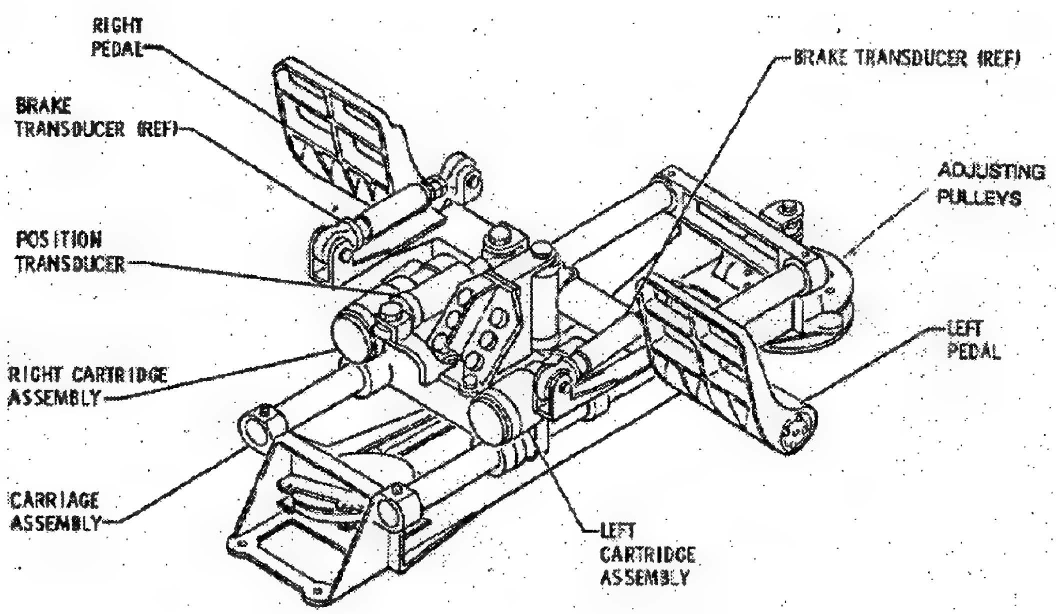


Figure 73 Lockheed F-117A rudder pedals, feel and transducers

6.0 CONTROL HARMONY

Traditionally, control harmony implies that the forces necessary to operate an aircraft in the three axes are neither too light nor too heavy relative to each other. The state of harmony is often stated in the general literature as a 1:2:4 ratio of aileron, elevator and rudder forces, or sometimes 1:2:3. Unfortunately it is not easy to discover what this actually means as practical guidance to the design of control feel, because the way in which each axis is used is quite different. MIL-STD-1797 states only the limiting maximum simultaneously applied forces for centre sticks as 25, 50 and 175 lbs for roll, pitch and yaw, a ratio of 1:2:7. However, in a combat aircraft large roll control inputs as well as small ones will be used quite frequently but briefly, whereas the pitch inputs will vary from small to large but tend to be applied for much longer periods. In the turn entry similar roll forces will tend to be used for all g levels from say 2 to 9. The customary use of roll non-linear gearings and spring force gradients further clouds the issue, since the feel of the roll response will be quite different for small and large roll inputs.

Dickinson (1953b) notes the complete lack of control harmony of the North American F-86A. The ailerons were exceptionally light and effective, but though the elevator was generally effective it was so heavy at higher speeds that considerable changes in aim in the late stage of dives on to a target were not easily achieved, and in transonic dives the stick force rose to over 100 lbs. The rudder was also very heavy. Nevertheless, pilots learned to adapt and did not find the disharmony unduly troublesome. Comments from the A.A.E.E. test centre of the R.A.F. included:

- " three controls completely out of harmony, but which help to make the aircraft an efficient fighting machine. The result is considered to be well worth the sacrifice of what has formerly been thought a pleasant if not essential characteristic."
- " it would seem unprofitable to return to our quest for some absolute formula for 'harmony'. Rather should we continue to treat each individual control on its own merits and make quite sure that it is up to its job."

While these pilots appeared willing to accept control disharmony for the sake of efficiency if necessary (even so, detailed improvement was considered necessary in certain areas), this was only in respect of combat aircraft. For cruising and instrument flight more typical of transport or other large aircraft, light roll and heavy pitch control force gradients made height keeping difficult in turns. Heavy roll and light pitch would also lead to inadvertent inputs to the pitch axis. In Lang/Dickinson, the conclusion was reached that "harmony of force levels between the controls seems relatively unimportant". The author's own experience over four decades of seven different combat aircraft types, in none of which was three-axis control harmony explicitly addressed, supports the notion that attention to the needs of each axis individually is as likely to result in satisfactory harmonisation of the whole as any other design policy.

6.1 Non-linearities

Dickinson (1953a) drew attention to the different feel requirements for "small" and "large" manoeuvres. In pitch, the feel characteristics must harmonise the tasks of trimming and adjusting speed, out-of-trim forces in high speed dives, small amplitude manoeuvring such as tracking, and gross manoeuvres, without either oversensitive or excessive stick forces. This depends on the response qualities of the airframe and the relative importance of such tasks as well as on the feel system, of course. As noted earlier in §3.2.3, it has been possible to achieve this with an essentially linear control feel with minimal friction and no explicit spring break-out force, but many of the feel systems described employ non-linearities in force gradient and break-out. In roll, the feel characteristic must allow small bank adjustments and low roll rates to be achieved easily without oversensitivity, while at the same time accommodating the maximum roll rates and accelerations within comfortable force limits. For aircraft with high roll performance this almost invariably requires the use of non-linear spring gradients, non-linear command gradients, or both. In yaw the requirements are much less demanding, and on many aircraft the rudder may be used very little except at low speeds for take off and landing. One task which should not be overlooked is full-time nosewheel steering, with its inherently divergent dynamics under heavy braking strongly influencing the requirement for pedal to nosewheel gearing non-linearity.

Examples of command non-linearities designed to enhance the harmony of input and response are given in Figure 74. Thomas illustrates the non-linear stick force versus g of the Argentinian IA-63 Pampas jet trainer, developed by Dornier with a pitch feel system based on the Alphajet. This ensured satisfactory trim and response around the 1g level, with enhanced static stability forces, while limiting the force at maximum g to comfortable values. This intention was frustrated by official rejection because it exceeded the maximum permitted Level 1 stick force per g gradient in the Mil. Spec, although it fell inside at larger inputs. The Alphajet also violated this requirement, but its handling was considered to be excellent, the pragmatic and correct view having been taken that the only final arbiter of handling is the pilot.

Non-linear roll command gearings have been used frequently. Mechanical devices were limited to a fixed shape, restricting the acceptable curvature to avoid excessive compensation at low speeds. In a FBW system, variable shapes are easily generated as in the Figure 74 example, similar to the BAe EAP and the Eurofighter 2000 systems. The linear baseline is used at low speeds, with a square-law increment added as a function of the scheduled roll rate response. The result is an easy and precise control of small amplitude manoeuvres and a low workload in rapid gross manoeuvres. The aircraft steady state response for the smaller inputs is relatively unchanged over the entire flight envelope. An identical non-linear structure is used in the nose wheel steering command.

Another factor in lateral stick harmony arises from the physical nature of the hand and its hold on the stick grip. Left stick is applied easily by pushing with the palm, while right stick is applied less easily by pulling with the fingers. It was not found necessary with traditional sticks to account for this (possibly it was never considered), but unequal left-right forces have made an appearance on some fly by wire sticks with the intention of making the apparent control effort uniform in both directions. Typically the maximum forces would be 10 lb to the left and 8 lb to the right, or with slightly less difference as in the F-117A noted in §5.3.

6.2 Spring gradient

In comprehensive g-seat simulation of low altitude high speed flight, A'Harrah found that pilot acceptance of the stick pitch feel characteristics was determined by the stick force-displacement spring constant rather than by the stick force or displacement per g, with Level 1 limits between 3 to 25 lb/inch. It is easy to arrange a q-feel system to stay well within these limits, and use of a non-linear gearing as in Figure 48 coupled with traditional trim variations can reduce the spread of force gradients to a range reasonably close to the middle of the suggested figures. This has been found highly satisfactory for this flight regime. Interestingly, the column force gradients of the Boeing 747 range from about 5 to 30 lbs/inch, though the latter figure would be twice as much were it not for the effective gear-

ing change caused by the control circuit stretch noted in §4.1.2 and 4.1.5.

A'Harrah found that the problem of arm jostling in turbulence with high stick sensitivities was not alleviated proportionately by high stick force gradients. This suggests use of the lower ranges of spring gradients for aircraft with low altitude roles. Lang/Dickinson proposed a minimum stick deflection per g of 0·5 inches for a fighter or attack type, and possibly twice as much for a low-g aircraft. A minimum of 1 cm per g (0·4 inches) was applied as a design rule for the Sepecat Jaguar, with very satisfactory results. This was retained in the BAe Jaguar digital Fly by Wire experimental aircraft, with a feel gradient of 5 lb/inch and stick force of 2 lb/g. With very tight pitch rate demand, this gave excellent handling, both in pitch tracking of a cine-weave target aircraft (typically 2 mils median error), and in high speed penetration of low altitude turbulence. Although less optimised aerodynamically for low altitude flight, the BAe EAP experimental aircraft also handled well at high speed in turbulence with a feel gradient of 7 lb/inch and 0·3 inches/g. The fixed feel spring gradients in both of these aircraft were also satisfactory in all other flight conditions.

There is a marked absence of flight-validated data to establish upper limits to satisfactory centre stick feel gradients to cater for all the tasks of an aircraft. Early experiments with rigid centre sticks (e.g. Russell/Alford) showed that a rigid stick was inferior to a displacement stick. The most comprehensive experiments on stick feel were those conducted by Black/Moorhouse on sidesticks (supported by many Air Force Flight Test School studies), showing clearly that some moderate motion was optimum. Sticks that are too stiff simply "feel wrong". An aspect of the sidestick feel harmony was the pilots' desire for relatively moderate aircraft response, probably because of the absence of a significant filtering effect typical of a conventional centre stick. The study by Citurs of controller requirements for uncoupled aircraft motion also includes a comprehensive survey of the literature on stick characteristics.

Figure 75 shows the stick force command functions of the F-16 (Garland), which evolved to eliminate the oversensitivity of its earlier schedules. The "acceptable roll command shaping" given in MIL-STD-1797 appears to be based on this and other schedules from aircraft with force sensing sticks. The roll performance of 308 degrees per second suggested here is not reached, because by the nature of the roll control law structure the command is backed off by the roll rate feedback, achieving balance at about 220 degrees per second. Taking account of this shows that the F-16 steady state roll response is up to 100% heavier than the Figure 74 schedule. As the latter was associated with an appreciably higher roll acceleration than the F-16, due to a smaller roll mode time constant, the difference in nominal acceleration sensitivity is even greater. A similar situation appears in the pitch command gain, contrasting with much lighter linear command gradients such as the 2·5 lbs/g found satisfactory with a central displacement stick.

It appears that one penalty of using a virtually rigid force stick tuned to give acceptable feel characteristics is a higher physical workload. In test pilot school courses in the variable stability Calspan Learjets in the U.S.A. and the ETPS Astra Hawk in the U.K., a regular demonstration is to select the rigid stick mode without telling the pilot or changing any other parameter. Usually the pilot fails to notice that the stick no longer moves, finds the aircraft now oversensitive and even PIO-prone, and attributes this to changes in the simulated dynamics. However, sensitivity is a function of the total stick travel, forward path gain, effective mode response time constant and command pre-filters, as well as the choice of displacement or force sensors.

The issue of appropriate gradients is significant for the stick design in future ASTOVL types of aircraft. An old VTOL specification requires a maximum feel gradient of 3 lbs/inch, whereas the standard minimum for conventional aircraft is 5 lbs/inch, apparently indicating that different gradients must be supplied for the jet-borne and wing-borne regimes. This is not consistent with experience in the experimental DRA VAAC Harrier (Fielding/Gale/Griffith) with a reduced travel centre stick and a single fixed feel spring gradient of about 5 lbs/inch. Completely seamless and easily controlled transition between regimes was achieved from take-off to fast flight to touchdown, by a wide range of Harrier, conventional and completely naive pilots. The 3 lbs/inch figure dates from the time of traditional sticks with typically ±6 inches travel, and of VTOL aircraft which required intense pilot effort with a large stick activity to stabilise them as well as to steer. The future ASTOVL aircraft, heavily stabilised and command augmented, will need basically just steering commands with little stick activity in the jet borne regime, vividly illustrated by the VAAC in single inceptor (right hand only) control mode with minimum workload.

6.3 Cross-talk

Transients due to stick switch operation and cross-talk between pitch and roll inputs were studied by Laycock *et al* and White. Operation of a switch on the stick grip produces transient inputs to an extent dependent on the magnitude of the operating force and its line of action relative to the grip pivot. It is naturally much easier to avoid a transient where the stick has substantial displacement and can be held relatively stationary while the switch is operated, than where the stick has negligible displacement and the switch operating force must be prevented from passing beyond the switch into the stick sensors.

It was found that human operators are rarely able to make precise demands along strictly Cartesian axes, i.e. left-right and fore-and-aft. The preferred control axes, along which minimum cross-talk occurs, are primarily determined by ejection seat/control geometry and grip shape. Conventional sticks with large displacements produce less inter-axis cross-talk than those with very small displacements. An extreme example of cross-talk was contributory to the first Gripen PIO accident. The axes of its central minimal travel wrist-operated stick were rotated 18 degrees to the left to align them with the right forearm. Initiation of maximum input PIO's, first in roll followed by one in pitch, was aided by the natural relay-like characteristic of such a stick (Gibson, 1995). As the pitch PIO diverged rapidly near the ground, the pilot reverted to an instinctive fore and aft arm action, pulling the stick directly back, inadvertently applying simultaneous full nose up and left roll commands and striking the left wing tip on the ground as the aircraft turned hard left.

Some concern was expressed about the potential pitch-roll cross-talk due to the centre location of the Shuttle Orbiter wrist action centre sticks, with 19° axis offset to align with the right arm. It was however equally felt that a straight alignment could also cause cross-coupling because the axis was *not* aligned with the wrist and arm. In the event, cross-talk has occurred but to an acceptably limited degree (Gilbert).

6.4 Stick "Transparency"

Essential factors in the achieved performance with any given stick include the overall cockpit environment and most importantly the handling qualities conferred by the FCS control laws. Regardless of these, the quality desired of a stick is that it should be transparent to the pilot, who should not be conscious of the stick *per se* even during a first flight on a type. Despite simple ground based experiments, often in a shirt sleeve laboratory environment, that may show improved accuracy of control in simple tracking tasks with a rigid force stick, the real overall flight environment has invariably shown that such a stick should never be considered. This is supported by Black/Moorhouse (and other references listed for further reading), based on in-flight experiments showing preference for a moderate stick force gradient and deflection.

The F-16 stick experience illustrates the profound importance of even a small amount of stick motion to precision control. Another example is given by Aiken, where a helicopter sidestick with ± 1·6 inches/±8 lbs in pitch and ±0·9 inches/±6 lbs in roll was superior to both 3-axis and 4-axis rigid sidesticks. It is understood that wrist displacement controllers are used in the Cheyenne helicopter, though aided by new instrument display techniques to maintain full mission effectiveness.

An important factor is the extent of wrist action as opposed to arm action in moving the stick. This is related not only to the angular rotation of the grip but to the distance of the pivot from the GRP. Myers *et al* discuss the appropriateness of wrist action for different types of control response: it is considered suitable for pulsive inputs, but not for control demanding prolonged application of force or displacement due to the smaller muscle systems. For the YF-22A, choice of the sidestick design was made only after a detailed comparison between of the F-16 stick and the GEC-Marconi stick in Figure 70. This has relatively much larger pitch displacements of 0·5 inches aft and 0·25 inches forward, though these are still small in conventional terms. The pivot point is many times further from the grip, which would appear to ensure that an arm action is required. The result was a clear decision for the latter stick, and it is also said to provide the desired transparency to new pilots. It is thought that the production F-22A stick will be similar, with provision for additional soft stop over-ride.

The original centre stick pivot in the SAAB Gripen was near the bottom of the grip, with nominal movements on the order of 10 mm. This caused considerable wrist fatigue, and the pivot has since been moved further down from the grip. One difficulty has been observed in some rig experiments with fighter sticks having different pivot locations for the same relatively small travel limits. A very short pivot length can cause confusing variations of the apparent feel stiffness depending on whether the force is effectively applied to the stick nearer the lower or upper part of the grip. This can occur as the hand is moved on the grip to operate different switches, and also whether the force is applied with the whole of the palm as in an arm action or with the top of the palm as in a wrist action. Such characteristics undesirably draw the attention of the pilot from the task in hand. No such difficulties were observed for a pivot 160 mm from the GRP. Comments made by many pilots about the EAP and Eurofighter 2000, typified by "natural and comfortable to fly", indicate that their centre sticks have the desired transparency in full.

Another factor that can improve transparency is whether the stick falls naturally to hand. Traditionally a fixed compromise position is used for the stick. Current fly by wire sticks are usually in the form of relatively compact line replaceable units as shown in Figure 70 and 72, and it is obvious that these could be mounted in adjustable positions rather easily. A centre stick might be repositioned on a track parallel to the seat back, or inclined further aft to bring it nearer the shorter pilots in the raised position, respecting clearance from the seat ejection trajectory. Sidesticks probably would not benefit from vertical adjustment, though it seems clear that adjustable arm and/or wrist rests are beneficial. In the North American X-15 with both a centre stick and a sidestick, the sidestick used for "ballistic" flight was adjustable to five fore and aft positions, said to be critical to cater for different pilots.

6.5 Stick dynamics

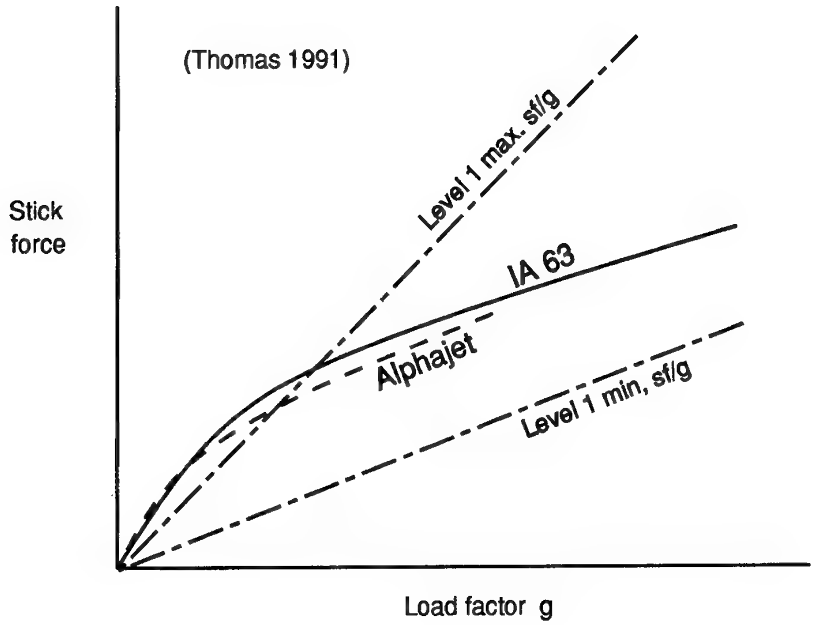
The dynamics of the stick and feel system influence the control harmony, but there is little design guidance. An excellent object lesson is given by two examples. The Grumman X-29 pitch stick was designed according to past conventional best practice with an 8 inch aft travel. The pitch response was poorly rated as sluggish, but halving the stick travel and doubling the feel stiffness greatly improved the ratings by an apparent improvement in aircraft response. It is possible that this problem was also related to poor matching of the pitch and roll feel gradients. Preflight fixed base simulation of the Lockheed F-117 received poorer ratings than suggested theoretically by the aircraft dynamics. With stick dampers added, the ratings improved to satisfactory and this was confirmed in flight. There is no theoretical or empirical design basis which would have predicted these improvements, and the changes were made at the suggestion of experienced test pilots. After 90 years of flight control development, it seems that there is still an element of art in the science and that there is no substitute for long and varied experience.

Morgan (1991) suggests that underdamping is unsatisfactory when the feel system natural frequency is both too high, being susceptible to bio-inertial feedback, and too low, when the sensation of a bobweight is present. Although this was based on helicopter controller studies, it appears to be supported by experience with fly by wire sticks without significant inertia which have been found to require good damping, and with the TSR-2 discussed above where the high inertia circuits required the addition of viscous damping. The latter is rather subjective, however, because no flights were made without the dampers in place.

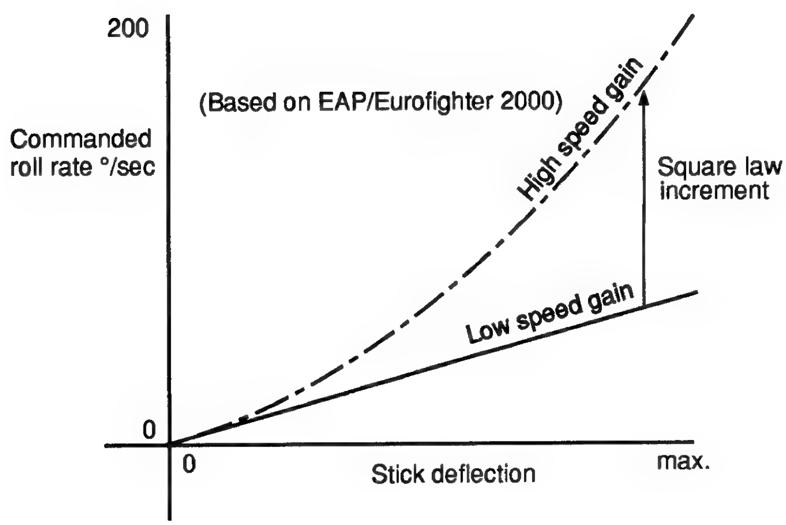
Formally, the equivalent lag or delay of a feel system, to which any damper is a major contributor, is often required by specification to be included in the overall high order delay of the complete axis response. This has inhibited the use of a circuit viscous damper in some cases to avoid the extra theoretical lag dynamics, yet it is a matter of experience that such a damper can greatly enhance the handling in some circumstances. One was part of the roll ratchet solution in the Jaguar FBW (Gibson 1995). The well damped central mini-sticks in the BAe EAP and Eurofighter 2000 are considered to be excellent pilot-airframe interface devices, as is the closely related sidestick in the Lockheed YF-22. Morgan (1988) describes the use of a stick command output notch filter to suppress the effect of an undamped stick response resonance, which would give the lowest possible feel lag dynamics, but it is unlikely that the resulting feel quality would be superior to that with an actual damper.

One current view (Anon, 1991 AGARD) favours the idea that the feel system dynamics (in the absence of bobweight effects) are not of great significance provided that the circuit natural frequency ω_n is at least about 2 Hz or preferably much higher. Watson/Schroeder suggest that the maximum effective stick inertia, $(32.2 \times 12 \times K)/\omega_n^2$, must be limited as a function of the stick force gradient K. Their formula gives a constant ratio for gradients above 4 lb/inch, corresponding to 13 rad/sec minimum natural frequency. For lower gradients decreasing to zero, the maximum stick inertia decreases linearly from 9 lbs to 6 lbs. The controlling factor for satisfactory stick feel at very low force gradients therefore is the inertia alone. Calspan data from their variable stability research aircraft support this formula, which was derived from helicopter data.

Another current view is that the feel system dynamics may be neglected for sticks with total travels of ±2 inches or more, but that for smaller travels the dynamics should be accounted for in the total aircraft dynamics. This is an attempt to resolve the specification dilemma by essentially dividing sticks into the categories of displacement or force sensing devices at a particular travel boundary. The convincing demonstration of the benefits of even the small amount of displacement on the chosen YF-22 stick compared to a quasi-rigid stick indicates perhaps that this is a subject on which the verdict is "not proven". In the likely absence of further definitive and comprehensive flight investigations, the only certainty is that the pilot will be the final arbiter of the total dynamic response and feel quality, however these interact.

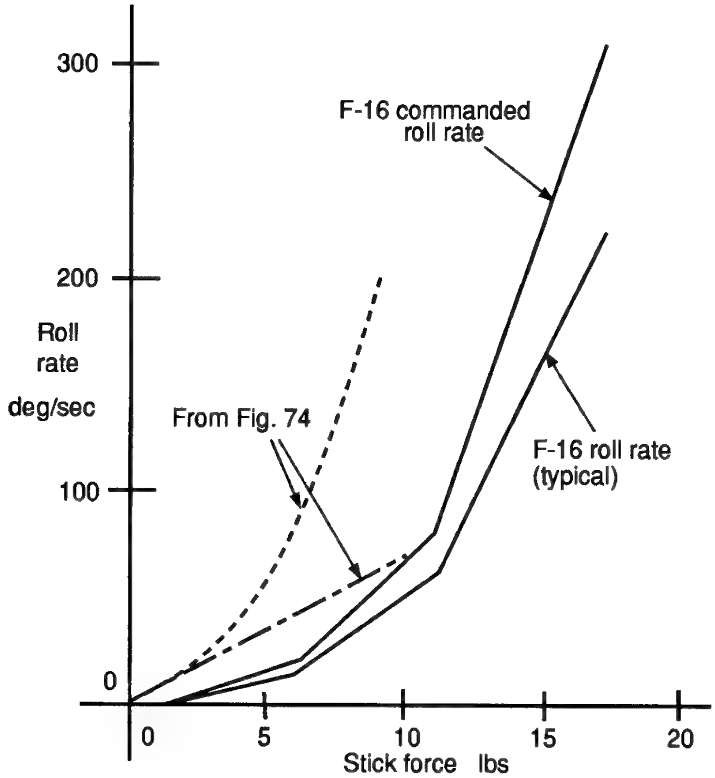


(a) Harmonisation of trim and manoeuvre pitch stick forces

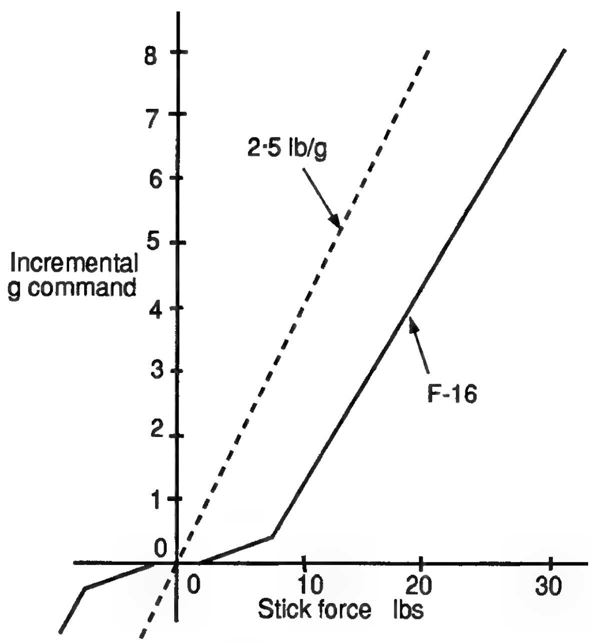


(b) Harmonisation of low speed and high speed roll rate command

Figure 74 Harmonisation of small and large manoeuvre forces by non-linear command gradients



Roll response gain variations



Pitch response gain variation

Figure 75 Sensitivity-related response gain variation with force and displacement sticks

7.0 THE FUTURE OF STICK AND FEEL

Surveying the subject from the past to the present illustrates the enormous changes that have taken place, though the focus of change has shifted through the aircraft from time to time. Initially the search was for good controllers. The airframe came next as methods were devised to make the aircraft more easily controllable through aerodynamic control surface modifications. As the aircraft flight envelope expanded, it became necessary to introduce power actuation with the accompanying artificial feel systems. Artificiality extended to the airframe dynamics with the introduction of limited stability augmentation. This expanded through control augmentation to full fly by wire, which became the centre of electronic, electro-hydraulic and digital signalling complexity though eliminating the mechanical complexity of the older control circuits. The associated feel systems have become extremely simple once again. As fly by wire technology matures, it is reasonable to consider whether the next focus of development might return again to the pilot's controllers. In view of the changes that have taken place, it would be unrealistic to suppose that entirely reliable forecasting of the future is possible, but some comments are offered.

One element has remained unchanged physically throughout this period, and that is the pilot. It will remain essential to adapt the controllers and feel system to the pilot, and not expect the pilot to operate devices that are inappropriate to the results of a few millions of years of human evolution. Nowhere has this been more obvious than in the saga of the rigid side-stick. Its obvious simplicity at one time was seized on by many outsiders to the world of flight control as the way of the future (particularly those who see the stick mainly as an obstacle to viewing their displays!), but it is a dead end. In discussions in 1980 with Laycock and Fullam at Farnborough about their detailed research in the RAE fly-by-wire Hunter with a rigid side-stick, they were critical of those who ignore the human's exceptionally precise control of limb movement but relatively coarse judgement of absolute force levels. Field calls for human-centred design with controllers that allow modulation through wrist, elbow and shoulder movements rather than even the very limited wrist movement of some controllers.

The defining distinctions between an arm-operated and a wrist-operated stick are not well established. How much movement in a stick is really the satisfactory minimum is not clear, nor how this might differ in centre and side sticks. As noted in §5, fly by wire limited displacement centre sticks have established a general measure of consistency in travels and force levels. These have proved to be extremely acceptable to pilots and there does not seem to be any reason to change them significantly. It is certainly clear that a wrist action centre stick has no place in a combat cockpit. The side stick issue has been clarified considerably by the YF-22A experience, discussed in §6, where the current stick geometry and travels were shown to be obviously superior to the current F-16 stick. This result should be expected also on the basis of the Black/Moorhouse report.

The selection of either a centre stick or a side stick is actually not a controller issue. The centre stick is clearly eminently suitable for the task, but the sidestick too has shown that it can be made to do the job. The real issue is a proper assessment of the overall cockpit design, of the seat, of the instruments, displays and switches, and how to fit them all together for the best operational effectiveness. Extreme reclined seats to allow very high g manoeuvres are inevitably associated with side sticks, but the recent trend to this idea might well be on the retreat. The pursuit of ever higher g capability (and hence weight) of the airframe seems less cost effective than highly agile missiles and helmet mounted sights. New developments in quick-response g-suits appear to have reduced the need for extreme seat reclining, the benefits of which may have been somewhat overstated in any case. It is the pilot's arms which hurt at 9g as much as anything else. The centre stick will be with us for many years to come. Vertical position adjustments would enable the pilot's leg to be used for an arm support as good as any other.

There is another widely observed characteristic of pilots that does not change, and that is a strong attachment to things with which they are familiar, associated with a tendency to pride in their ability to handle a difficult airframe. That is not surprising, considering the investment they make in learning to operate their aircraft to the best advantage. It should not be allowed to stand in the way of the development of different techniques, provided that these do not conflict with fundamental human instincts. This issue will undoubtedly be raised in future ASTOVL aircraft designs by the existence of the Harrier pilot community. Many years ago, the author was involved in the design study and simulation of a twin engined tilt-nacelle supersonic STOL fighter with a conventional stick, throttle and tilt lever. The aerodynamic and engine controls were truly integrated by the fly by wire system where the stick commands had direct control of three engine parameters. The flight path was controlled with the stick and airspeed by the tilt controller. With the appropriate briefing, it was extremely easy to fly through the transition to a slow landing for all pilots, except a Harrier pilot who complained that it was not like a Harrier, tried to fly it like one and failed. However, one surprising complaint was that "it seems too easy"!

The same philosophical objection could be heard in the VAAC Harrier two-lever control research (Fielding *et al*) where a similar principle was used, that is vertical path control with the stick from normal flight all the way to the hover and landing, and horizontal thrust and speed control with the left hand controller at all speeds down to zero. There was no direct pilot control of either the engine thrust or the nozzle vector angle in the hover and transition regime. The intention of the VAAC research was not primarily to improve the Harrier but to develop control methods for future ASTOVL aircraft which were physically incapable of being controlled like a normal Harrier. It sometimes seemed that this stated intent was the only way to make the project acceptable in some quarters. In flight, again the "conventional" pilots found it very easy and natural, and had no difficulty with the entire transition process. Harrier pilots tended to approach it with the conviction that they could perform better with their normal direct three-lever control, but to be converted when they actually flew it. In fact the VAAC could out-accelerate or decelerate the standard Harrier by a substantial margin. They also found that their fears of confusing the required control actions, which were quite unlike the standard Harrier, were groundless. These points are made not to promote any particular ASTOVL control technique, since others are also feasible, but to show that new developments with a potential influence on future controller design can be subjected to pressures based on views which are based on perfectly valid experience but which are not well informed on alternative possibilities. This should be resisted.

Equally, when experience has shown or confirmed that new techniques are deficient in some aspect of piloting, the problem should be addressed. Current fly by wire controllers have become functionally simple in the extreme (except for the Boeing 777 by choice), but although this has worked extremely well it is not a wholly unmixed blessing. For example, in combat aircraft with a fixed spring feel stick in which full travel is always used to reach a "carefree" envelope limit, variations in allowable g due to the carriage of certain store loads can be achieved by variations in the control law, but this leads to some difficulty in matching stick force per g or in store-release transients. A more direct approach would be to have a variable position aft stop. Though a fully variable q-feel seems not to be necessary, a variable stiffness force gradient could be useful in some cases such as flight refuelling where a reduced aircraft sensitivity is desirable. The issue of a lack of dual stick interconnection remains a controversial one, though currently driven by the difficulty of achieving it. A similar situation exists regarding autopilot back-

feed to throttle controls, apparently desired by a large proportion of pilots (Field). Future left hand controllers for ASTOVL aircraft could well benefit from the ability to vary their characteristics as a function of flight regime, providing for example the functions of pure thrust control, speed or acceleration control, or translational rate command.

Development is currently under way to produce active fly by wire sticks which can perform all the above changes. Digitally controlled, they will be able to generate any linear or non-linear force gradient function, alter the force gradients, vary the soft or hard stop positions, provide variable position detents, provide parallel trimming, and replicate exactly the effects of stick interconnection or back-feed from an autopilot. Reliability can be enhanced by a reversionary spring whose feel gradient can be higher than the minimum active gradient. Though they are some way off a productionised state, their existence may provide the next focus on change that has always continued to enhance aircraft handling qualities over the past century.

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PART 2: ANALYZING STICK AND FEEL SYSTEMS USING ANALYTICAL PILOT MODELS

1.0 OVERVIEW

Part 1 has discussed in detail the evolution and design of aircraft force-feel systems, from the Wright Flyer to modern, high-performance aircraft. They have described the "hows" of force-feel system design. The following sections will attempt to approach the "whys" of design, with a particular emphasis upon the modern, irreversible flight control system. It will become apparent that the answer to the question of "why" must inevitably involve a detailed discussion of the human element in the flight control system, i.e., the pilot.

Section 2 begins with a review of some of the problems and promises associated with irreversible flight control systems. Section 3 presents a closed-loop perspective concentrating on analytical models of pilot dynamics including representations of the neuromuscular system. Section 4 treats the handling qualities issues surrounding force-feel system design, for both fixed-wing and rotary-wing vehicles. In addition, the role which force-feel systems play in the roll ratchet phenomenon is discussed along with a brief treatment of low-frequency controllers and control sensitivity. Section 5 deals with pilot performance in vibrating and accelerating environments and Section 6 discusses a few of the effects of force-feel system nonlinearities. A final summary and discussion of future directions are presented in Section 7.

2.0 IRREVERSIBLE, FLY-BY-WIRE FLIGHT CONTROL SYSTEMS

2.1 Overview

At the risk of belaboring the obvious, it is useful to repeat the well-known fact that the operational envelopes of high performance aircraft, from transports to fighters, have expanded to the point that the human pilot is no longer capable of providing the forces required to deflect the aerodynamic force/moment effectors. The necessity for the ingenious design and implementation of devices to effectively amplify the power of the human arm and leg (geared, blow down, servo and spring tabs, etc.) has been all but obviated by the introduction of fully-powered and irreversible controls (e.g. Roskam, 1991). Irreversibility means that some artificial force-feel system has to be implemented in the cockpit. Failure to do so would deny the pilot important information or cues regarding the state of the aircraft and, in particular, the loads which were being imposed by his/her control actions. Irreversible hydraulic controls are also typically employed on many larger rotorcraft, where the sizeable aerodynamic loads generated at the main and tail rotors are simply too large to be compensated for with simple devices (Prouty, 1989).

The question of just what might constitute the dynamics of "ideal" artificial force-feel system dynamics naturally arises at this juncture. To this end, it is useful to consider the dynamics of a typical mechanical force-feel system for fixed-wing aircraft. Figure 1 typifies such a system in somewhat simplified form (McRuer and Johnston, 1975). The linearized force-displacement dynamics associated with the system of Fig. 1, shown in Fig. 2, can be given as

$$\frac{\delta_{ST}}{F_s} = \frac{R_s^2}{I_T} \frac{(s+K_s/C_s)}{\left[s+\frac{K_b}{C_s}\left(\frac{1}{1+K_B/K_s}\right)\right]\left[s^2+\frac{(K_s-K_B)}{C_s}s+\frac{(K_B+K_s)}{I_T}\right]} \tag{1}$$

where F_s represents pilot applied force and δ_{ST} represents resulting stick displacement or position. With representative values for the parameters in Eq. 1, the resulting transfer function essentially describes a low-pass filter, with a break frequency determined by the simple denominator pole. However, the inclusion of bob-weight dynamics can be shown to move this pole to higher frequencies. The upshot of this modeling is that the dynamics of the mechanical force-feel system of Fig. 1, can often be adequately described by a second-order system, i.e.

$$\frac{\delta_{ST}}{F_s} \approx \frac{K_F}{s^2+2\zeta_F\omega_F s+\omega_F^2} \tag{2}$$

The majority of research on force-feel systems has concentrated upon the linear dynamics of Eq. 2, e.g. the natural frequency and damping ratio. The literature review of Wasicko and Magdaleno (1965), and the experiments of Graham (1967) provide two of the few modern studies of the effects of nonlinearities such as force breakout, force-displacement hysteresis, nonlinear control sensitivities, etc. on human operator performance. This will be discussed further in Section 6.

2.1.1 Promises

With the requisite technology, one can take the next logical step and consider a fly-by-wire system in which the various pushrods, cables, pulleys and bellcranks implied by Fig. 1 are replaced by electrical connections, moving, as it were, from the domain of Newton to that of Maxwell. Such systems have evolved from the conceptual to the operational, not only in high-performance military aircraft such as the F-18 (Burton and Kneeland, 1981) but also in commercial transports such as the Airbus A320 (Corps, 1986), and in military rotorcraft, e.g, the RAH-66 Comanche (Kandebo, 1995).

Given the genesis just described, it is understandable that the force-feel characteristics of most modern fly-by-wire flight control systems are still describable by Eq. 2. However, the freedom offered by electronics has encouraged a number of

important modifications: (1) the use of *force* as opposed to *displacement* as a command variable to the flight control system, (2) the ability to vary the parameters of the force feel systems with some ease, and (3) the possibility of altering in almost arbitrary fashion the relationship between the force applied by the pilot and the displacement of the control stick.

The use of force as a command variable was initially associated with force or isometric (non-moving) control sticks (e.g. Black and Moorhouse, 1979). However, force command sticks need not be isometric. The well-known example of the F-16 side-stick controller evolving from an isometric to an isotonic (moving) device while still retaining it's force command characteristics is well known (Ibid). The possibility of providing control stick cues, e.g forces, which are dependent upon aircraft response variables also has a long history. The bobweight, providing stick forces proportional to vehicle acceleration, is perhaps the simplest and best known example. The relative ease in which one can create and modify, via electronics and servo systems, the force-feel characteristics of mechanical controllers is demonstrated by Hegg, et al (1992) and Hosman and van der Vaart (1988).

Feedback of aircraft response variables to the cockpit controller defines what have been called "active" or "smart" control sticks. However, topologies for other motion feedbacks were discussed in detail over fifty years ago in one of the famous BU AER Reports, *The Artificial Feel System*, (Anon, 1953). There, it was proposed that aircraft response variables such as airspeed perturbation and normal acceleration could be sensed and reproduced as stick forces to provide what was termed "force stability augmentation". This force stability augmentation was in addition to "motion stability augmentation" in which motion variables were sensed and fed directly to the control surfaces without feedback to the control stick. This BU AER document was essentially the first detailed, systematic discussion of "active" as opposed to "passive" control sticks, a discussion which continues today (e.g., Repperger and Frazier, 1983; Hosman and van der Vaart, 1988; Hosman, et al, 1990).

Interest in the force-feel characteristics of control manipulators in rotary wing vehicles has increased for reasons similar to those for fixed-wing vehicles. In particular, the design freedom offered by fly-by-wire and fly-by-light systems has led researchers to reexamine rotorcraft cockpit controls, from the standpoint of force-feel characteristics and control integration (e.g., Sinclair, 1982; Aiken, 1986; Kruk, et al, 1986; Watson and Schroeder, 1990; Morgan, 1990). It is interesting to note that the nature of the restraints (spring gradients, viscous damping, etc.) can vary widely in rotorcraft while still allowing acceptable handling qualities and performance. For example, many pilots of the UH-1 prefer to disconnect the force-trim system entirely in hover, and to fly with only stick inertia and dry friction providing force-feel (Watson and Schroeder, 1990; Morgan, 1990).

The simulation effort of Citurs (1984) provided an in-depth investigation of the effect of some controller nonlinearities upon the performance and handling qualities of high-performance fighter aircraft. These documents (Vols. I and II) contain a wealth of information about a specific application i.e., fighter cockpit control devices for uncoupled six degree-of-freedom motion and in addition provide an excellent review of the pertinent literature.

2.1.2 Problems

Given the available technology, the experience of nearly a century of powered flight, and the fact that the sensing and actuation capabilities of the human pilot are essentially unchanging, one might ask why force-feel system design is still an important issue. One possible answer is contained in the question, itself. Namely, that while the performance capabilities of modern aircraft have increased exponentially since the Wright Flyer, those of the human pilot have not. The bandwidths of modern flight control systems have begun to approach those of the pilot's own sensing and actuation systems, often with surprising and unpleasant results. The pilot-vehicle phenomenon known as "roll ratchet" which occurs in fixed-wing aircraft, was unheard of two decades ago, but has become the object of a considerable amount of research (e.g. Johnston and McRuer, 1987). This phenomenon has been linked to the pilot's neuromuscular dynamics. Engineers considering the design of future aircraft such as high speed civil transports and hypersonic vehicles are concerned with vibration feedthrough to the control stick and the interaction of elastic modes with the pilot's neuromuscular system, (e.g., Chan, et al, 1992). The deleterious effects of the latter phenomenon in a modern subsonic transport were evident in a PIO incident in an early flight test of the Boeing 777 aircraft (Dornheim, 1995).

A particular problem associated with vehicle handling qualities involves the question of inclusion or exclusion of the dynamics of the force-feel system in the specification of vehicle open-loop characteristics such as the Bandwidth Criterion (Hoh, 1988) and the Smith-Geddes criterion for susceptibility to pilot-induced-oscillations (PIO) (Smith and Geddes, 1978). Data and analyses can be found which support both approaches (e.g., Smith and Sarrafian, 1986; Bailey, Powers and Shafer, 1988; Mitchell, et al, 1992). This is anything but a trivial issue for the simple reason that inclusion of the force-feel system in a specification means the force-feel system dynamics, e.g., Eq. 2, are now to be considered as part of the vehicle. The phase lags accompanying the force-feel system dynamics now produce an additional effective time delay. Since such delays have been shown to sharply degrade a vehicle's handling qualities, (e.g., Berry, et al, 1980; Smith and Bailey, 1982), considering the force-feel system as part of the vehicle can yield a significant difference in predicted handling qualities as compared to excluding these dynamics. This important topic will be revisited in a later section.

Problems which eventually have been traced to the nature of the force-feel system or manipulator restraint are not restricted to higher frequency pilot inputs. For example, flight tests of a short takeoff and landing (STOL) research aircraft (Hindson, et al, 1981) uncovered a flight path control problem involving the use of a throttle flight director and throttle manipulator. Under manual control with a flight director in landing approach, the vehicle exhibited a low frequency (0.13 Hz) oscillation in flight path. The problem was later analyzed (Hess, 1983) and shown to be attributable to a mismatch between the throttle manipulator restraints and the dynamics of the effective vehicle.

2.2 Conclusion and assertion

The problems and, in some cases, apparent inconsistencies in the determination of what constitutes ideal or even acceptable force-feel systems in aircraft and rotorcraft can be traced to a criticism which might be leveled at handling qualities research in general. Namely, from the time of Gilruth's pioneering studies (Gilruth, 1943) the handling qualities discipline has, by and large, been appealing to an inspection and categorization of *open-loop* vehicle characteristics to shed light upon what is demonstrably a *closed-loop* phenomenon. Through exhaustive simulation and flight tests, this approach has succeeded reasonably well, and useful handling qualities specifications have resulted (e.g., Anon., 1969; 1980; 1989; 1990). However, the experimental matrices for investigating parameters thought to influence vehicle handling qualities, and force-feel system characteristics are among these, can be extremely large. Concentrating upon linear characteristics, alone, the parameter space for force-feel system design includes natural frequency, damping ratio, control sensitivity, isometric and isotonic constraints, and force and displacement commands.

With the preceding in mind, the following section will address the "why" of the force-feel system design, with an eye toward the closed-loop pilot/vehicle system. The advantages and limitations of this approach will become clearer as the discussion proceeds.

3.0 FORCE-FEEL SYSTEMS - A CLOSED-LOOP PERSPECTIVE

3.1 Antecedents

Research by psychologists in the area of aircraft controls during and immediately after World War II typically concentrated upon such topics as maximum forces that could be exerted by a human, reaction time as it delayed the pilot's response, optimal design, placement and movement of cockpit controls, optimal force gradients, etc., (e.g., Jenkins, 1947; Orlansky, 1949). Speed and accuracy of movement were also of interest, with the work of Fitts as a prime example (Fitts, 1954). Interest in modeling the behavior of a human as an active feedback control device also began during World War II, when engineers and psychologists were attempting to improve the performance of pilots, gunners and bombardiers. In order to design satisfactory manually controlled systems, these researchers began analyzing the neuromuscular characteristics of the human operator. Their approach, (e.g., Tustin, 1947) was to consider the human much like an inanimate servomechanism with a well-defined input and output. This work was the birth of what has come to be called the "control theoretic" model of the human operator or pilot. This method of quantifying control-related human behavior has evolved into one of the fundamental modes of thinking on the part of most manual control practitioners, (e.g., McRuer, 1980).

In the mid 1950's psychologists were also interested in the role which *proprioceptive feedback* played in human motor response, and, in particular, in the positioning of controls (e.g. Gibbs, 1954,; Weiss, 1954; Bahrick et al, 1955a, 1955b). Proprioception and proprioceptive feedback refers to sensory information about limb position and the rate and intensity of muscular contraction which is continuously and unconsciously provided to the human peripheral and central nervous system. This information will play a pivotal role in the modeling descriptions to follow.

As mentioned previously, the work reported in the BU AER document *The Artificial Feel System* marks one of the first systematic treatments of the manner in which different feel system characteristics can be represented in control theoretic terms with block diagram representations. In this BU AER document, the pilot was considered as a *force producer*, with the force-feel system incorporated into an "equivalent airframe". Figure 3, taken from the report, exemplifies this modeling approach. Here a closed-loop pilot-vehicle system for longitudinal control is represented. Note the definition of both "force" and "motion" stability augmentation, which together with the basic, unaugmented airframe presents the aforementioned "equivalent" airframe. In the force stability augmentation, airspeed perturbation, $u(t)$, and normal acceleration, $a_z(t)$, are sensed and fedback as forces applied to the control stick, creating what is now referred to as an "active" control stick. In Fig. 3, the force-feel system is assumed to be a simple spring as shown in Fig. 4, with K_δ representing the spring constant, including stick-to-control surface gearing.

Figure 5 represents a simplification of Fig. 3, with the various force and motion feedbacks subsumed into the block labeled "equivalent airframe". The pilot-vehicle representation of Fig. 5 was more than adequate for the early work in identifying human operator dynamics in compensatory tracking tasks, (e.g., McRuer and Krendel, 1957). The manipulators in these tasks were either unrestrained or restrained with simple springs. As such, they exhibited natural frequencies well beyond the highest frequency for which accurate spectral measurements of the signals in Fig. 5 were possible at the time, e.g. 4-5 rad/s.

Approximately eight years after the publication of WADC TR-56-524, a more detailed study of human operator dynamics in compensatory tasks was published (McRuer, et

al, 1965). This research concentrated upon the effects of forcing function bandwidth and controlled element dynamics upon human operator describing functions (transfer functions and remnant). One very important product of the reported research was the "crossover model" of the human operator or pilot. This model essentially describes the ability of the human to adapt to different controlled elements and random appearing command inputs with different bandwidths. Also noteworthy was the diagrammatic representation of the human operator reproduced here in Fig. 6. Note that the possibility of "manipulator dynamics" other than the simple reciprocal gain $1/K_s$ of Fig. 3 are now considered. What is more important is that Fig. 6 shows a feedback of *limb position* in the human operator model and an implicit *combination* of human operator and manipulator dynamics. This is an obvious departure from the representation of Figs. 3 and 5. In the experiments of AFFDL-TR-65-15, the manipulator was a small, spring restrained side-stick. The natural frequency of the device was still well beyond the highest measurement frequency, now 13.8 rad/s. Since the measurements of AFFDL-TR-65-15 were expressed in terms of the combination of operator and controlled element, termed $Y_pY_c(j\omega)$, the issue of defining the human output as force or displacement was unnecessary.

The effect of the type of manipulator restraint, i.e. spring restrained, pressure (isometric) or unrestrained, upon human operator dynamics and tracking performance was also investigated shortly after the publication of AFFDL-TR-65-15 (McRuer and Magdaleno, 1966; Magdaleno and McRuer, 1966). In the parlance of aircraft attitude control, the first of the studies emulated a roll-tracking task, the second, a pitch tracking task. The controlled elements were the stereotypical K, K/s and K/s^2 employed in AFFDL-TR-65-15. The research generally confirmed the superiority of the non-moving pressure or isometric controller as first documented by Gibbs (1954). In addition, and for the first time, the effects of manipulator restraint upon $Y_pY_c(j\omega)$ were documented. A number of the conclusions of these studies are worth repeating.

1.) For all controlled elements the high-frequency phase lag with a free-moving manipulator is greater than that with the pressure manipulator.

2.) For position control tasks (i.e. $Y_c = K$) the pilot can operate as a position output device....The force-displacement characteristics are largely swamped by a tight position feedback loop.

3.) For $Y_c = K$ the human operator can control the force on an unrestrained very large inertia (stick), effectively ignoring the extraneous position cues. System performance is little different that for the pressure controller. However, he is not as successful for $Y_c = K/s^2$; there is a large performance decrement from the pressure control configuration.

Clearly, the results just summarized point to the inadequacy of simply modeling the human pilot as a force producer, and lumping the manipulator or force-feel system with the vehicle dynamics. As an example, consider the case of the human attempting compensatory tracking with K/s^2 controlled element dynamics with a large-inertia, unrestrained control stick (manipulator dynamics = I/s^2, with I representing moment of inertia). Considering the human as purely a force producer and lumping the manipulator dynamics with that of the controlled element produces an effective controlled element $Y_{ce} = KI/s^4$. The dictates of the crossover model of the human operator would require the human to generate triple lead equalization for this effective controlled element (McRuer and Krendel, 1974). This has been shown to be beyond the capabilities of the human operator, e.g., the human operator has been shown to have extreme difficulty in controlling third-order dynamics (Jex and Allen, 1970). However, as reported in AFFDL-TR-66-72, the tracking task was quite difficult with this manipulator constraint, but it could be accomplished. Any further questions about the human's ability to use both force and position in control tasks were firmly laid to rest the work of Herzog (Herzog, 1968, 1969).

Herzog's work involved what he termed the "matched manipulator" concept shown in block diagram form in Fig. 7. Here the dynamics of the manipulator, described by the transfer function θ_M/T_h (stick displacement to torque input applied by human), were "matched" to those of the controlled element and applied force was used as an input to the controlled element. This matching was done electronically (an "active" or "smart" stick). Assuming the human could sense the manipulator displacement, θ_M, Herzog reasoned that these dynamics would effectively appear in the feedback loop of the human's proprioceptive system. With a large enough gain associated with this sensed manipulator position, simple block diagram algebra showed that an approximation to the reciprocal of these dynamics would appear in the numerator of the operator's own closed-loop dynamics, effectively canceling the dynamics of the controlled element. Thus, regardless of the actual controlled element dynamics, the task would appear to the human operator to be simple position control, i.e., $Y_c \approx K$. Herzog demonstrated the validity of his approach with a variety of controlled elements. Performance with the matched manipulator was consistently superior to that without. The matched manipulator concept was later refined and improved by Merhav and Ya'acov (1976). In particular, the performance benefits were extended to disturbance regulation as well as input tracking.

The concept of providing vehicle output information to the pilot via proprioceptive cues was also investigated by Gilson and Fenton (1974), albeit with a different philosophical approach than Herzog. Here the researchers constructed and flight tested a control manipulator which featured a rectangular moving slide or "finger" mounted on the grip of the controller. The displacement of this slide represented errors in selected aircraft response variables, e.g. angle of

attack, from some desired reference value. When no error was occurring, the slide was flush with the grip. If say, angle of attack decreased from the desired trim value, the finger would protrude proportionally on the forward part of the grip. An increase in angle of attack would cause the finger to protrude on the aft part of the grip. These protrusions would provide the pilot with proprioceptive cues and allow corrections to be made without reference to a visual display of angle of attack. The device was found to work quite well in laboratory and flight evaluation.

It should be noted that many of the issues involved with the design of force-feel system for aircraft flight control are also common to the design of force-reflecting teleoperated robots, (e.g., Sheridan, 1992). As a case in point, Sheridan repeats what he refers to as "Jex's criteria for 'feel' of hand controls and time delay in simulators". Henry Jex (Jex, 1988) postulated the following four critical tests for achieving virtual reality in the feel of hand controls, such as those for teleoperated robots, aircraft, automobiles, etc:

1.) With all other simulated force set to zero, when the mass or inertia of the simulated hand control is set to zero, it should feel like a stick of balsa wood, i.e massless.

2.) When pushed against simulated hard stops, the hand control should stop abruptly, with no sponginess, and it should not creep as force continues to be applied.

3.) When set for pure Coulomb friction, the hand control should remain in place, without creep, sponginess or jitter, even when repeatedly tapped.

4.) When set to simulate a mechanical centering or "detent" and moved rapidly across the detent, the force reversal should be crisp and give a realistic "clunk" when no perceptible lag or sponginess.

3.2 Neuromuscular system modeling

The experimental studies just summarized provided fairly convincing evidence that a more detailed modeling of the neuromuscular system of the human operator or pilot was warranted if a more accurate and useful representation of the human were to be available for pilot-vehicle analyses including force-feel system design. Early representations of human pilot dynamics such as given by the "precision model" (McRuer, et al, 1965) treated the neuromuscular system through the introduction of pole-zero combinations as shown below:

$$Y_p = K_p\, e^{-j\omega\tau} \left(\frac{T_L j\omega + 1}{T_I j\omega + 1}\right) \left\{\left(\frac{T_K j\omega + 1}{T_{K'} j\omega + 1}\right)\right\} \cdot \left\{\frac{1}{(T_{N_1} j\omega + 1)\left[\left(\frac{j\omega}{\omega_N}\right)^2 + \frac{2\zeta_N}{\omega_N} j\omega + 1\right]}\right\} \tag{3}$$

The terms within the large { } are intended to represent low and high frequency effects of the neuromuscular system. The low frequency dipole involving the time constants T_K and $T_{K'}$ create the low frequency "phase droop" noted in all the describing function measurements of AFFDL-TR-65-15. The terms inside the large [ ] represent the high frequency effects of the neuromuscular dynamics. Of course, as mentioned previously, the spectral measurements which yielded the describing functions of this report only extended to 13.8 rad/s, so the high frequency dynamics presented in Eq. 3 are only approximations.

Further research in the late 1960's and early 1970's allowed more detailed representation of human neuromuscular dynamics, (e.g., McRuer, et al, 1968a; McRuer, et al, 1968b; McRuer and Magdaleno, 1971). In particular, the latter NASA CR described experiments in which electromyograms were used to determine average muscle tension in tracking experiments involving a hand manipulator and rudder pedals. This led to describing function measurements of the muscle-manipulator combination. Based upon this research, a refined structure for the pilot-manipulator combination was derived and is shown in block diagram form in Fig. 8. The model shown here has central equalization appropriate for rate dynamics ($Y_c = K/s$). Appropriate changes can be made to the central equalization to accommodate other controlled element dynamics, again following the dictates of the crossover model. In addition, only two manipulator restraints are assumed: free-moving or pressure (isometric).

A detailed description of the physiology behind the model of Fig. 8 is beyond the scope of this document. Nonetheless, at least a brief description is in order. Starting from the far left, one has a visually sensed error signal, appropriate for a compensatory tracking task. This error is input to a block labeled "retinal and central equalization", intended to describe activity in the central nervous system which provides the basic ability of the human to generate lead, lag, etc, appropriate for the controlled element dynamics at hand. The term "retinal equalization" is intended to allow for rate sensing that may be produced directly from the retina (McRuer, et al, 1968a). Alpha motor neurons innervate extrafusal muscle fibers to produce contraction or relaxation of the muscles in the limb effecting control. The alpha motor neuron command (α_c) is obtained as the difference between the output of the central equalization and that of "effective joint angle sensors" in the limb effecting control. As the name implies, these proprioceptors provide information about the angular

relationship between limbs such as the forearm and upper arm, etc. The alpha motor neuron command is summed at the spinal cord level with the output of other proprioceptors called "muscle spindles". These sensors are essentially stretch receptors within the muscles which are sensitive to changes in muscle length that accompany force application. The block labeled "muscle/manipulator" dynamics includes a pure time delay and three poles, the latter representing the dynamics of the limb and manipulator (only unrestrained in this case). Note that the diagram is somewhat misleading, since if a pressure or isometric manipulator is used, the joint sensor feedback loop is removed, and the spindles are essentially sensing force due to muscle contraction, rather than manipulator position.

For a pressure manipulator, the transfer function between manipulator output (now a force) and α motor neuron input could be approximated as:

$$\frac{c}{\alpha_c} \approx \frac{K_{NM}\left(1+\frac{s}{P_{SP}}\right)e^{-\tau_{NM}s}}{(1+T_{N_1}s)\left[1+\frac{2\zeta_N s}{\omega_N}+\left(\frac{s}{\omega_N}\right)^2\right]} \tag{4}$$

These dynamics are quite similar to the high frequency dynamics of Eq. 3, with the addition of a zero and time delay (the latter of which could be subsumed into the τ of Eq. 3). In the measurements of NASA CR-1757, the numerator factor $(s+P_{sp})$ was located at a frequency well above that of ω_N. As an example, Fig. 9 shows measured Y_p with a first-order sub-critical controlled element and a hand manipulator. The parameters T_K $T_{K'}$, T_I and T_L are retained from Eq. 3, with the high frequency dynamics now given by Eq. 4.

Of course, force-feel system dynamics can rarely be categorized as simply isometric or unrestrained devices. Further evolution of the model of Fig. 8 can be found in work by Johnston and Aponso (1988), as shown in Fig. 10. Here explicit manipulator dynamics are shown and the possibility of force or position sensing is now indicated.

It is interesting to note that other human operator modeling procedures can produce the apparent neuromuscular system dynamics evident in experimental describing function measurements without explicitly modeling the neuromuscular system, e.g., the optimal control model (OCM) of the human operator (Kleinman, et al, 1970). As opposed to the isomorphic models proposed by McRuer, et al, the OCM of the human pilot is algorithmic, based as it is upon the solution of a linear, quadratic, Gaussian regulator-estimator design. Human limitations are included by way of a pure time delay in visual inputs, which themselves are corrupted with multiplicative observation noise and the use of a quadratic index of performance which weights both tracking performance and control effort. Despite the fact that no explicit modeling of the human neuromuscular system is included, the predicted human operator transfer functions can be shown to exhibit high frequency amplitude and phase characteristics which have been associated with the dynamics of the neuromuscular system (with negligible manipulator dynamics). Figure 11 shows one such OCM generated transfer function (Hess, 1987). Note the similarity between this figure and Fig. 9. Results such as these raise an interesting philosophical issue. Namely, while the high frequency dynamics associated with measured human operator transfer functions may be attributable to the neuromuscular system, their existence is actually part of the human's equalization capabilities, essentially no different than low-frequency lead or lag equalization, etc.

The idea of the neuromuscular system with its inherent proprioceptive feedback loops defining at least part of the human's equalization capabilities, i.e. his/her ability to adapt to different vehicle dynamics, leads somewhat naturally to a modeling approach offered by Hess, (e.g., Hess, 1985). While certainly not elevating this approach to the status of neuromuscular system modeling, Hess' "structural" pilot model is somewhat unique in that it hypothesizes that *all* of the human's fundamental equalization capabilities derive from proprioceptive feedback. For example, in this model, low-frequency lead equalization on the part of the human is not hypothesized to occur through time *differentiation* of a visual input, but through time *integration* of a proprioceptive one. Hess claims that if one accepts this seemingly equivalent and perhaps trivial restructuring of the manual control paradigm, a certain unification occurs in viewing a number of disparate experimental phenomena. In the past, this model has been used to describe the adaptive nature of the human pilot (Ibid), to provide a rationale for human operator pulsive control behavior when tracking with higher-order controlled element dynamics (e.g., K/s^2, K/s^3) (Hess, 1979), to describe human pilot preview control (Hess and Chan, 1988), to model the pilot's use of motion cues (Hess, 1990a), to provide a theory for aircraft handling qualities (Hess and Yousefpor, 1992) and to analyze the effects of visual display quality on perceived vehicle handling qualities (Hess, 1995a).

The structural model of the human pilot was developed using experimental data in which the dynamics of the manipulator were negligible. In attempting to analyze force-feel system problems (where manipulator effects are obviously not negligible) it was found that the original model structure needed to be modified. The resulting model is shown in Fig. 12 (Hess, 1990b). A valid criticism of this model is that it pays scant attention to any detailed modeling of proprioceptive sensors such as muscle spindles or joint angle sensors. In fact, the neuromuscular dynamics, *per se* are modeled by the block labeled "neuromuscular system". The "proprioceptive compensation", G_I, creates the low-frequency lead, lag or gain equalization dictated by the crossover model. The possibility of biodynamic feedback is also included to model arm-bobweight effects. Table 1 demonstrates how different force-feel systems can be handled with this approach. This model will be revisited in a later section.

Perhaps the most detailed and focused pilot neuromuscular modeling research that has been attempted in the past decade is that of van Paassen (van Paassen, 1990, 1991, 1992, 1994). This work was motivated by the interest which the Faculty in Aerospace Engineering at the Delft University of Technology express in active sidestick controllers, (e.g., Hosman and van der Vaart, 1988; Hosman, et al, 1990). Figure 13 is a simplified representation of van Paassen's model, including models for the neuromuscular system, the pilot's cognitive control, the side stick, and the aircraft. The neuromuscular system model is further divided into submodels for muscle, skin, and limb inertia, including neural and muscle control feedback paths. These submodels are shown in Fig. 14. Through a series of well-controlled laboratory experiments involving human subjects using a sidestick controller in a roll tracking task, the parameters of the all the submodels were determined. The purpose of the model as described by van Paassen is to accurately describe manual aircraft control using a sidestick, a goal which is certainly valid given current recent interest in these controllers, (e.g., Corps, 1986; Hegg, et al, 1992). In addition, the model has been exercised in an analysis of the roll ratchet phenomenon (van Paassen, 1992).

Finally, it is also interesting to note that problems with closed-loop instability in teleoperated devices have led to neuromuscular systems modeling similar to that discussed herein for aircraft flight control, (e.g., Kazerooni and Snyder, 1995). The importance of force feedback in teleoperated devices also has led to the study of sensory substitutes for this cue, (e.g., Massimino and Sheridan, 1992).

4.0 HANDLING QUALITIES ISSUES

4.1 Military specifications

The ultimate objective of research in the area of force-feel systems is to establish principles, guidelines and specifications for engineering design. That is, the flight control or handling qualities engineer needs to know how the characteristics of a force-feel system will impact vehicle handling qualities, or lacking this, at least how to apply existing handling qualities specifications to proposed vehicles. Unfortunately as will be seen, military handling qualities specification have not treated this subject in a consistent manner.

4.1.1 Fixed-wing vehicles

Military Specification MIL-F-8785B (Anon., 1969) for fixed-wing aircraft lists a number of force-feel system static requirements regarding maximum stick forces, breakout forces, etc. Of primary interest in this report are the dynamic characteristics, where allowable lags between control surface response and cockpit control *force* inputs over a specified frequency range are specified. In addition, it is required that the cockpit control *deflection* should not lead the cockpit control force for any frequency of force amplitude. At first blush this may seem an impossibility, however, the incorporation of bobweights can create this condition. In terms of damping, the specification simply requires that all control system oscillations shall be well damped.

It is not uncommon for modern high performance aircraft to exhibit unstable "open-loop" or bare airframe dynamics. Such vehicles require full-authority stability and command augmentation systems (SCAS's) for operation. The dynamic characteristics of these highly augmented aircraft can be distinctly different from those of unaugmented ones, and will almost invariably be of higher order. To encompass these vehicles in handling qualities specification, changes to MIL-F-8785B were required. To this end, Military Specification MIL-F-8785C introduced the "lower order equivalent systems" concept, (e.g., Hodgkinson, 1982). In this later specification, airframe manufacturers were required to match the higher order frequency responses with lower order classical forms, which could then be addressed via the older specification. Included in this lower order equivalent model was an equivalent time delay, obviously used to approximate the higher-frequency effects of many different flight control components, *including* those of the feel system.

Some six years after the appearance of MIL-F-8785C, Smith and Sarrafian (1986) published a paper involving some flight test results with the X-29A forward-swept-wing demonstrator aircraft, which called into question much of the previous treatment of force-feel systems in MIL-F-8785C. Since this paper is a pivotal one and led to a number of further experimental efforts, some detailed discussion is warranted.

The X-29A is a dynamically unstable vehicle and possesses a relatively complex flight control system. This system accepts cockpit stick position as its command input. As just mentioned, the philosophy of MIL-F-8785C dictates that the feel system must be included in determining the lower order equivalent system. The feel system for this aircraft could be represented by Eq. 1. In particular, in the roll axis,

$$\frac{\delta_{ST}}{F_s} = \frac{K_F}{s^2+2(0.7)(13)s+13^2} \qquad (5)$$

Note the relatively low undamped natural frequency of 13 rad/s. These dynamics contributed approximately 0.10 s of equivalent time delay in terms of MIL-F-8785C, which, in turn, was approximately 45% of the overall equivalent time delay for the vehicle. According to MIL-F-8785C specification which requires including the force-feel system dynamics in demonstrating compliance, this vehicle should have received level 3 handling qualities on the Cooper-Harper scale of Fig. 15. (Harper and Cooper, 1986). With the feel system dynamics ignored, however, the vehicle would be predicted to be level 1/level 2 region. Subsequent flight test results with the X-29A vehicle did not support the handling qualities categorization dictated by MIL-F-8785C. However, if the feel system dynamics were neglected, the correlation was much better. In addition, as discussed in the Smith-Sarrafian paper, the overall assessment of the handling qualities of another high performance aircraft, the F/A-18 was consistent with MIL-F-8785C if the dynamics of the force-feel system were not included.

The results just discussed led to a series of flight tests with the USAF/Calspan NT-33 variable stability aircraft in visual approach and landing tasks, also discussed by Smith and Sarrafian. Two feel systems were investigated, identified as a "slow" system ($\zeta_F = 0.7$, $\omega_F = 13$ *rad/s*) and a "fast" system ($\zeta_F = 0.7$, $\omega_F = 26$ *rad/s*). By adjusting time delays downstream of the feel system, the total equivalent delays of the flight control systems, including each of the force-feel system were forced to be identical. Somewhat surprisingly, the fast feel systems was unflyable near the ground because of a divergent lateral PIO, while the slow feel system exhibited a slight PIO tendency, but was controllable. The guidelines of MIL-F-8785C would have placed both of these configurations in the level 3 region. These results, in turn, provided the impetus for another brief series of flight tests, this using the Calspan Learjet in-flight simulator. The results of these and the previous tests led the authors to conclude that "Correlation of pilot rating results with the MIL-F-8785C time delay boundaries is poor when the feel system is included, as required by MIL-F-8785C. Excellent correlation is obtained, however, when the overall time delays in a position-command flight control system are referenced to stick position, not stick force, therefore excluding the feel system delay contribution." Smith and Sarrafian concluded their paper with a brief pilot-vehicle analysis using the structural pilot model (Hess, 1985) to suggest how feel system effects could impact handling qualities as demonstrated by their data.

It should come as no surprise that the Smith-Sarrafian paper was responsible for generating considerable experimental and analytical activity by handling qualities researchers. A well-documented series of flight tests were initiated, again using the USAF/NT-33 variable stability aircraft (Bailey, et al, 1988). The test matrix included: control system command input (force or position), feel system natural frequency (26, 13, and 8 rad/s), analog stick filters with dynamics identical to those of the feel system, pure time delays (0.055, 0.110, and 0.174 sec), roll mode time constants, and roll command gains (adjusted to give specific steady-state roll rates per stick force). Focusing upon the force-feel system effects, the study results did not completely support those of the Smith-Sarrafian paper. While demonstrating that the force-feel system should be viewed as a unique control system element, the MIL-F-8785C requirement using the stick force input for equivalent time delay definition *was* substantiated.

In another closely related study, Johnston and Aponso (1988) conducted a very thorough examination of manipulator and feel system characteristics in a fixed-base, laboratory simulation. The experimental matrix was quite large and included the measurement of pilot transfer functions. The results indicated the relative merits of stick displacement versus stick force command in terms of effective time delay, closed loop pilot-vehicle bandwidth, tracking performance, PIO tendencies, and pilot's neuromuscular mode peaking. Force sensing was found to minimize forward loop dynamic lag, as would be expected. In addition, tracking performance with force sensing sticks was found to be superior to that obtained when a position sensing stick was used. However, some command prefiltering was found to be necessary to prevent roll ratchet, a phenomenon to be discussed in Section 4.2. The position sensing stick, on the other hand, reduced or eliminated any tendency for roll ratchet, provided the force-feel system natural frequency was high enough. It was recommended that the principal dynamic mode for the force-feel system should be greater than the pilot's neuromuscular mode which is on the order of 12-13 rad/s. The position command also reduced or eliminated the need for command prefiltering. All these results applied equally well to center or sidesticks. The authors found no performance differences or pilot preferences between feel systems with natural frequencies as low as 14 and 26 rad/s. As in the study by Bailey, et al, (1988), handling qualities rating degradation with increasing effective time delay was found to be consistent with the criterion of MIL-F-8785C.

To add somewhat to the confusing state of affairs, the current military specification for fixed-wing vehicles, MIL-STD-1797A (Anon, 1990) generally specifies that the feel system be excluded from the dynamics of the aircraft. However, some requirements are applied both including and then excluding the force-feel system (Mitchell, et al, 1994). This is demonstrated in Table 2, from Mitchell et al (Ibid), where the dynamic requirements for force-feel systems in MIL-STD-1797A have been summarized. In light of some of these non-uniformities, Moorhouse has informally suggested refinements to the MIL- STD-1797A criteria, especially as regards the Smith-Geddes PIO criteria (Moorhouse, 1994).

Potsdam and Hodgkinson (1990) offer a very interesting and decidedly closed-loop analytical approach to assessing the data of the preceding studies. A pilot-vehicle analysis using a simplified version of the neuromuscular system model of Fig. 8 was undertaken. Rather than considering the pilot rating to be dependent upon the *open-loop* vehicle equivalent time delay (obtained from the lower order equivalent system), a new "modified equivalent delay" was obtained after considering the pilot's closure of a position loop around the manipulator. The resulting correlations with pilot rating were improved somewhat when compared to those predicted when the feel system dynamics were included in the calculation of the equivalent time delay in open-loop fashion. The authors point out that their modest improvement in correlation must be weighed against the added complexity of pilot neuromuscular system modeling. Nonetheless, the study is a good example of a closed-loop analytical approach.

The philosophy behind the modeling approach of Hess (1990b), discussed briefly in Section 3.2, is similar to that of Potsdam and Hodgkinson. In a purely analytical study, the model of Fig. 12 was employed in investigating changes in pilot-vehicle characteristics (i.e. $Y_pY_c(j\omega)$) that accompanied changes in the restraints, output command, and bandwidth of the manipulator or force-feel system. In addition, the model was used to investigate the roll ratchet phenomenon to be discussed in Section 4.2. The rationale behind the modeling

study was to demonstrate that the salient changes which have been shown to occur in the pilot-vehicle system open loop transfer function Y_pY_c can be qualitatively captured by the model of Fig. 12, with relatively few changes in the model parameters.

As an example of the modeling procedure, the first two rows of Table 3 show the model, controlled element and force-feel system parameters for a pair of tracking experiments involving a force-feel system with force command (sensing) and position command. The experiments in question were reported by Johnston and Aponso (1988). Figure 16 shows the model-generated Bode plots for $Y_pY_c(j\omega)$. Figures 17 and 18 show the experimentally derived Y_pY_c's, with the dashed line in Figure 17 representing a hand faired curve through the phase data of Fig. 18. The qualitative similarity between the phase relationships for these two experimental conditions is reflected in the model results of Fig. 16, namely, that the force sensing force-feel system results in smaller phase lags at higher frequencies. Although not emphasized in the figures, the amplitude characteristics of the Y_pY_c's is also captured by the model. Note in Table 3 that *no* model parameters were changed in making this analytical comparison. Only the physical input to the controlled element (force or position) as reflected in the position of switch 2 in the model of Fig. 12 was changed. Comparisons were also made between isometric (pressure) and unrestrained manipulators, and between so-called "fast" and "slow" position sensing force-feel systems (ω_F = *26 and 14 rad/s*), with the model capturing the qualitative changes in $Y_pY_c(j\omega)$ in each case. Although not pursued by Hess, it would be interesting to determine if changes in pilot opinion rating between the different configurations could be captured using a handling qualities prediction technique offered by Hess and Yousefpor (1992).

Mitchell, et al (1994) have addressed the issue of whether to include or exclude feel-feel system dynamics in Mil-Spec compliance and have come down on the side of including them, at least until more data is available to address the issue in more direct fashion. To justify this position, the authors first present Fig. 19, which demonstrates the effect of manipulator and simulation facility on the average crossover frequency, ω_c, of $Y_pY_c(j\omega)$. Clearly, the data indicate the force-feel system is *not* transparent to the pilot. Next the authors consider a subset of the data summarized by Bailey, et al (1988), and shown here in Fig. 20. This data represents the pilot ratings received in the USAF/Calspan NT-33 aircraft in a series of landing approach tasks. The vehicle dynamics are identical for all the configurations. The parameters which are changed are the nature of the stick command sensing (force or position) and the natural frequency of the force feel system (ω_F in Eq. 2). The authors state that the scatter in the data may be due in part to different values of control sensitivity. As can be seen from Fig. 20, the data coalesce best when the equivalent time delay is computed including the force-feel system.

One important and succinct conclusion of the study of Mitchell, et al, regarding force-feel system design, is that based upon the data analyzed in their study, an acceptable force-feel system is attainable as long as the effective stick natural frequency (ω_F) is above 10 rad/s, or the effective mass (I) is less than 5 lbm, with a stick damping ratio above 0.3. The authors add that more detailed design guidelines require much more experimental data.

4.1.2 Rotary-wing vehicles

The current rotorcraft handling qualities specification (Anon., 1989), employs a bandwidth requirement on the flight control system, as does MIL-F-1797A. In this requirement, a control system bandwidth, ω_{BW}, and phase delay, τ_p, are defined using the transfer function between pilot input and attitude response. Level 1-3 handling qualities regions are then defined in this two parameter space, e.g. Fig. 21. The definition of pilot input here is treated by stating simply: "It is desirable to meet this criterion for both controller force and position inputs," (Mitchell, et al, 1992).

Watson and Schroeder (1990) conducted a fixed-base simulation and flight test aimed at determining the effects of force-feel systems on rotorcraft handling qualities near hover. The vehicle utilized for both the fixed-base (ground) and flight simulation was the NASA/Army CH-47B variable-stability helicopter. The task was a roll-attitude regulation (via cockpit display) in the presence of simulated turbulence. The vehicle as simulated possessed a rate-command/attitude hold SCAS. As in previous studies, the effect of inserting dynamics equivalent to those of the force-feel systems in the command path was investigated. The experimental matrix was generated by varying force-feel system damping ratio and undamped natural frequency (Eq. 1) from 0.34 to 0.64 (ζ_F) and 4.9 to 11.5 rad/s (ω_F). In addition, the command variable to the flight control system could be either force or displacement. Finally, the authors also considered independent variation in stick inertia. That is, they considered Eq. 2 expressed as

$$F_s = I\ddot{x} + b\dot{x} + kx \qquad (6)$$

with I representing the stick inertia. In terms of the parameters of Eq. 2, with $x \equiv \delta$, one has $K_{FS} = 1/I$, $\zeta_F = b/[2(kI)^{0.5}]$, and $\omega_F = (k/I)^{0.5}$. Root locus evaluation of the pilot-vehicle system was also undertaken using the pilot model of Fig. 10.

Among the conclusions of this study was that considering only the natural frequency and damping ratio of the feel-system dynamics results in an inadequate quantification of their effects on handling qualities, i.e., all three parameters in Eq. 6 (I,b,k) must be considered. In addition, although force sensing appears to be beneficial, in general, the "feel" of the control stick was more important to the pilots than whether force or displacement sensing was being used. The location of dynamic elements in the command path seemed to have

little influence on pilot ratings, and again, stick "feel" was the determining factor. Summarizing, pilot comments suggested an upper boundary of approximately 0.15-0.2 slugs effective inertia (*I*), with 1.0 lbf/in force gradient (*1/k*) in Eq. 6. Variations in damping ratio from 0.3 to 0.6 had little effect on performance and handling qualities.

As an example of the general lack of agreement between researchers in this well-defined area, Fig. 22 shows effective stick inertia plotted versus the square of the reciprocal of the force-feel system undamped natural frequency. This plot is not included in the paper by Watson and Schroeder but was included in an oral presentation of these research results. Also shown on the plot are the recommended boundaries from the Johnston and Aponso study (Johnston and Aponso, 1988). As can be seen, the recommended boundaries not only are disparate, they are orthogonal in this parameter space. However, the data does suggest a composite boundary, with the level 2-3 handling qualities area defined by the "1st quadrant" of the orthogonal shaded boundaries. It is interesting also to note that the Watson-Schroeder bound would support the notion of the acceptability of tracking with zero force gradient in the cyclic control (i.e., $(1/\omega_F)^2 = \infty$) as mentioned previously .

Another series of rotorcraft flight tests involving force-feel system characteristics was reported by Morgan (1990). This study used the Institute for Aerospace Research Bell 205A variable stability helicopter. The experimental variables were the static and dynamics characteristics of a conventional center-mounted cyclic controller. The stick force displacement characteristics were given by Eq. 2, with $K_F = G_s\omega_F^2$, with G_s being a product of a constant sensitivity and ω_F^2. In addition, an isometric stick was included in the experimental matrix. With the exception of the latter stick, all were position sensing devices. As opposed to the Watson-Schroeder study, the damping ratio of the force-feel system now emerged as an important parameter. In particular minimum desirable values were obtained associated with the lowest and highest ω_F values. These ζ_F values were approximately 0.22 for the low ω_F (5.4 rad/s) and 0.37 for the high ω_F (26.2 rad/s). The different ζ values were used primarily to create different effective time delays for the force-feel system (defined as $2\zeta_F/\omega_F$). The low ω_F value for ζ_F created an undesirable sensation of a bobweighted stick, while the high ω_F value induced a biodynamic coupling with an idiosyncratic mode of the Bell 205A referred to as a "mast rocking" mode.

Morgan tentatively proposed yet another handling qualities boundary, this time in ζ-ω_n space. Interestingly, enough, he did not uncover the stick mass boundary (*I*) of Watson and Schroeder. However, this may have been due to the fact that a constant static force-deflection relation was enforced by the introduction of the factor G_s. Morgan did note the stick position cues afforded by the non-isometric configuration were a definite plus in terms of handling qualities.

4.2 The roll ratchet phenomenon

The roll ratchet phenomenon alluded to in the preceding sections entails a high-frequency (12-15 rad/s) closed-loop oscillation which can occur in rolling maneuvers of high-performance aircraft. The name derives from the sensations which the pilots often describe as "jerkiness" in the aircraft's rolling response. This phenomenon deserves special attention here since its existence has been strongly linked to the characteristics of the force-feel system, (e.g., Johnston and McRuer, 1987; Hess, 1990b; van Paassen, 1994). Although pitch ratchet is rarely discussed, some evidence for it can be found in pilot comments. For example, in reviewing pilot comments in the data base for what is termed the LAHOS study (Smith, 1978), one can find one pilot stating "Had a fast, staircase type approach to final response...There was a high frequency hunting for the ground." Another pilot states "Get a high frequency bobble in flair....Very high frequency PIO evident in flare. Doesn't really affect task much. Annoying." These comments, directed toward longitudinal control, are suggestive of a ratcheting problem. Apparently the rarity of such occurrences in longitudinal control explains the lack of attention which they have received in the literature.

As pointed out in the handbook accompanying MIL-STD-1797A (Hoh, et al, 1982), roll ratcheting has been reported as occurring on many aircraft with command augmentation systems. This includes the F-4 Survivable Flight Control System (SFCS) aircraft, the YF-16, F-16, and the A-7D DIGITAC. In addition, it was experienced on the USAF/Calspan NT33 variable stability aircraft during the LATHOS study (Monagan, et al, 1982). Indeed, this latter study is the one most responsible for bringing the problem of roll ratchet into the mainstream of discussion in the handling qualities community. The fly-by-wire Jaguar aircraft also exhibited a mild roll ratchet (Gibson, 1994). As an example of a roll ratchet encounter, Fig. 23 shows two steady rolling maneuvers performed in the YF-16, the first with a roll ratchet encounter, the second without.

The cause of roll ratchet has been widely debated. It's occurrence appears less amenable to the analytical techniques which can be used to predict a vehicle's susceptibility to its lower-frequency sibling, the PIO, (e.g., Smith and Geddes, 1978; Hess and Kalteis, 1991). It should be emphasized that pilots are quite unambiguous in differentiation a PIO from a roll ratchet (Monagan, et al, 1982). One of the first analyses aimed at determining a cause for roll ratchet was that of Chalk (1983). By employing a simple pilot-vehicle analysis using the crossover model of the human pilot and a pure rate-command vehicle dynamics ($Y_c = K/s$), Chalk demonstrated that instabilities in the frequency region noted in roll ratchet could be obtained using values of pilot effective time delay of approximately 0.4 s. His analysis assumed that the high rolling accelerations induced by a vehicle with excess roll damping ($Y_c = K/(s(T_R s+1))$, $T_R << 1$) induced the pilot to close the roll control loop on roll *acceleration*, rather than attitude or rate.

Johnston and McRuer (1987) and Johnston and Aponso, (1988) felt that the similarities between measured roll ratchet frequencies and those associated with the amplitude peaking in the human's closed-loop neuromuscular system were not coincidental. Based upon a series of fixed-base laboratory tracking tasks, Johnston and McRuer concluded that

1.) The roll ratchet phenomenon is a closed-loop pilot-vehicle system interaction in which the pilot's neuromuscular system plays a central role.

2.) Ratchet tendencies can be detected in carefully designed fixed-base tracking tasks by taking into account the influence of higher frequency motion disturbance on the pilot's effective time delay.

3.) Ratchet tendencies are most severe on force-sensing side-stick manipulators.

By way of example, Fig. 24 from NASA CR-4111 is a Bode plot of measured $Y_pY_c(j\omega)$ characteristics showing neuromuscular system amplitude peaking beyond 10 rad/s. According to the authors, this peaking, alone, would not be indicative of a roll-ratchet oscillation unless the corresponding phase lag were close to -180 deg. The data indicate considerably more negative phase lags. However, these data were for fixed-base tracking. As a first-order correction to the phase data to account for rapid rolling motion (where the roll ratchet phenomenon usually occurs) a phase increase of 0.1ω rad was considered as an approximation to the effects of an inner-loop roll-rate closure by the pilot. With this adjustment, the phase lag around the frequency for amplitude peaking is near -180 deg. Johnston and Aponso also suggest that roll ratchet tendencies can be sharply reduced or eliminated using position sensing as opposed to force sensing controllers.

As mentioned in Section 3.2, Hess (1990b) also attempted to shed light upon the roll-ratchet phenomenon. The third and fourth rows of Table 3 list the model and force-feel system parameters utilized. Note that motion feedback is now considered, and both force and position sensing force-feel systems are modeled. For the position sensing case, the vestibular gain K_m was chosen to produce a minimum damping ratio of approximately 0.15 on the most lightly damped mode in Y_pY_c. This value represents a trade-off between stability and the high-frequency phase lag reduction, which is the *raison d'etre* of motion feedback (Hess, 1990a). Initially for the force sensing case, the vestibular gain K_m was also chosen to yield the minimum damping ratio just described. In examining the resulting Bode plots, no significant amplitude peaking was seen to occur in either case. However, if the same K_m obtained for the position sensing case was used for the force sensing, a significant amplitude peaking was seen. This is summarized in Figs. 25 and 26, showing $Y_pY_c(j\omega)$ for the position and force sensing systems with and without motion cues. This value of $K_m = 0.4$ for the force sensing was larger than the value selected by the minimum damping ratio case. In addition, Fig. 26 indicates that the phase lag is nearly -180 deg for the use of a force sensing stick with motion. Thus, the excessive amplitude peaking for the force sensing with the larger motion gain results in considerably more oscillatory tendencies in the closed-loop.

However, before suggesting any indictment of the force sensing stick, one must provide some rationale for the larger motion feedback gain, since a reduction in K_m would sharply reduce the roll ratchet tendency. It was suggested by Hess (1990b) that in large amplitude rolling maneuvers where roll ratchet typically occurs, motion is a very compelling cue, especially if oscillatory behavior is developing. As opposed to visual and even proprioceptive cues, motion cues cannot be easily ignored. Thus this modeling effort suggests that roll ratchet may be traced to the interaction of (1) vehicle dynamics with broad K/s-like dynamics, (2) the force sensing feel system and (3) motion cues. Hess felt that each may be necessary for the existence of roll ratchet.

Some measured pilot-vehicle transfer functions from the data of the experiment summarized by Bailey, et al (1988), and presented by Mitchell et al, (1992) tend to support the amplitude peaking hypothesis, with one reservation. Figures 27 and 28 are the Bode plots for $Y_pY_c(j\omega)$ transfer functions from flight test for cases in which roll ratchet occurred, and for cases in which it did not occur, respectively. The significantly higher "neuromuscular mode" amplitude peaking in the former transfer functions is evident. It should be noted that the traces of control stick inputs in the ratchet cases show ratchet frequencies commensurate with the frequencies for peaking in Fig. 27. However, what is absent in these figures is evidence of phase lags near -180 deg in the frequency region where the amplitude peaking occurs. It is also pertinent to note that the roll ratchet cases shown were all obtained with *position* sensing controllers, a contradiction of both Hess' implication of force sensing control as being a necessary condition for ratchet (Hess, 1990b) and one of the conclusions of Johnston and Aponso (1988) mentioned above. Likewise some of the no ratchet cases were obtained with force sensing controllers. In addressing the issue of the phase lags not being near -180 deg in the frequency range where amplitude peaking occurred, the authors noted that roll ratchet is a nonstationary phenomenon related to pilot compensation variations during the course of a run. Hence, it is possible that variations in pilot compensation during the course of the run, sufficient to cause ratchet for a time, would not be seen in the averaged pilot data for the whole run.

Finally, it should be pointed out that the mild roll ratchet experienced by the Jaguar aircraft and discussed by Gibson (1994) occurred only when the control stick was gripped lightly, and could be prevented by a firm grip on the stick. A lateral bob-weight analysis identified the necessary control law change, and with the addition of a control stick damper, the ratchet was eliminated. These particular roll ratchet encounters are interesting in that they occurred at nearly zero

roll rates with a position sensing control stick with large displacement. Since the ratchet was seen to occur with only light or negligible stick force applied by the pilot, neuromuscular mode peaking would not seem to be a contributory factor.

4.3 Low frequency controllers

Most of the studies just outlined have dealt with manual control tasks requiring relatively high bandwidths from the standpoint of manual control, e.g., 2-5 rad/s. There exists interesting research dealing with lower bandwidth systems in which the nature of the manipulator restraints have effected performance and/or handling qualities. One of these, mentioned briefly in Section 2.1.2 focused on throttle control of a STOL aircraft in landing approach (Hindson, et al, 1981; Hess, 1983). It was suggested in the latter study that the "ideal" effective vehicle or controlled element may depend upon manipulator configuration and restraints. The STOL vehicle in question was flown with a typical "backside" control technique, i.e., engine thrust, manipulated via the throttles was used to control altitude, with vehicle pitch attitude, manipulated with the control column used to control airspeed. A flight director was used in the landing approaches, and included commands for the throttle.

Following established flight director design guidelines (e.g., Klein and Clement, 1973), the effective vehicle transfer function with the director in operation was $\delta_d/\delta_{th} \approx K/s$, where δ_d represents flight director symbol translation and δ_{th} represents throttle movement. However, as mentioned in Section 2.1.2, and shown in Fig. 29a, flight path performance with this director was unsatisfactory in that significant oscillations in flight path occurred. By referring to the structural model of the human pilot, Hess showed that the proprioceptive feedback signal for this controlled element was approximately that of a pure gain. Hess further hypothesized that the throttle position (overhead with no support for the pilot's arm), restraints (no centering characteristics, with Coulomb friction) and the low frequency characteristics of the throttle motion, was far from ideal in terms of accurate proprioceptive feedback. As part of the study of Hinson, et al, the flight director dynamics were changed to resemble that of a gain in the frequency range of interest. The flight path oscillations disappeared, as shown in Fig. 29b. In attempting to explain these results, Hess theorized that, in changing the effective vehicle transfer function for the flight director law to that of a pure gain, i.e. $\delta_d/\delta_{th} \approx K$, the required proprioceptive feedback was *rate*, and not *position* and proprioceptive rate sensing would not be as compromised by the manipulator characteristics just outlined.

In an experimental study of submarine depth control, Boller and Kruger (1979) employed a force sensing, but movable, control column and compared performance with an active and passive manipulator restraint system. In passive (active) mode the controller displacement (force) was integrated to provide a depth-rate command to the control system (i.e. controller force or displacement actually was an *acceleration* command. The simulated submarine possessed a stability augmentation system with what might be called a "depth-rate command" dynamics. Figure 30 shows time histories of a depth transition maneuver emphasizing the low frequency nature of the control activity.

In the active controller configuration, the achieved depth rate was reflected in the position of the column. However, as opposed to other studies in which similar active controllers have been evaluated, (e.g., Hosman and van der Vaart, 1988; Hosman, et al, 1990), no significant differences in performance, objective workload and subjective operator ratings were noted between the active and passive controllers. The primary difference between this study and previous ones was that the effective vehicle dynamics were unfortunately ***not appreciably changed*** by the active controller. This was because of the fact that in the either mode, the controller commanded depth acceleration and consequently, in either passive or active mode, the effective vehicle dynamics (depth-rate/operator input) were approximately K/s. Thus the nearly identical performance and handling qualities should be expected.

The purpose of reviewing this last research study was to emphasize that a closed-loop perspective is vital if one is to achieve reasonable and effective results in designing force-feel systems. That is, merely providing the human with proprioceptive information (in this case submarine depth-rate through manipulator displacement) may not always bring the desired improvement in performance and handling qualities.

Force-feel systems can provide vital low-frequency information about vehicle states without explicit feedback of the state in question. A classical example is "positive stick force stability" which, when interpreted as a requirement, means that dF_s/dV, the slope of the stick-force trim velocity diagram, must be negative when the aircraft is in trimmed flight. Here positive stick force is defined as a "pull" (e.g., Perkins and Hage, 1949). This characteristic imparts important proprioceptive information to the pilot, i.e. in flight around trim (zero stick force) a steady pull (push) on the control stick will presage an increase (decrease) in airspeed from the trim or equilibrium value. Positive stick force stability is particularly important for low speed flight such as approach to landing. However, some SCAS designs, e.g. pitch rate command/attitude hold, effectively remove such stick force stability which then has to be created artificially, (e.g., Mooij and van Gool, 1978).

The example just discussed demonstrates that an attempt to improve one aspect of an aircraft's handling qualities will often adversely affect the proprioceptive input the pilot receives from the force-feel system. Another pertinent example involves a recent analysis of a "supermaneuverable" fighter aircraft (Hess, 1995b). The object of the work was to reduce the PIO-proneness of the vehicle in question while making as few changes as possible to the flight control architecture. The approach taken was to introduce a filter

immediately downstream of the control stick which would effectively change what was an alpha-command system to an alpha-rate command system. The advantages of this change are discussed by Hess (Ibid). While a PIO analysis using the methods of Smith and Geddes (1978) and Hess and Kalteis (1991) both predicted a definite reduction in PIO-proneness, with the stick filter, it was realized that an important proprioceptive cue was denied the pilot. That is, in the original alpha-command system, stick force/position provided information regarding commanded angle of attack in maneuvering flight. While this information was also available from cockpit instrumentation, obtaining it visually during combat maneuvering would present significantly increased pilot workload. With the alpha-rate command system, the proprioceptive angle of attack information is lost. That is, a pulsive stick input produces an angle of attack change, but after the pulse, the stick is back in trim position where no proprioceptive force or displacement cue is provided for the pilot. Thus, some modification of the force-feel system would be necessary in order to retrieve this cue. One possibility is to actively employ the stick force trim system in a manner that would allow stick *position* to indicate angle of attack. This simply means that the zero-force stick position would be driven by measured angle of attack. Thus, even though alpha-rate is being commanded, the pilot would be aware of the actual alpha via the zero-force position of the stick. This approach has yet to be evaluated in simulation or flight test.

4.4 Control sensitivity

For irreversible, fly-by-wire control systems, control sensitivity refers to the multiplicative factor or gain which can be applied to the control stick output (e.g. a voltage). However, this sensitivity is usually expressed in terms of a specific vehicle transfer function, as will be seen. It has long been known that, in manual control tracking tasks, the human operator is able to accommodate a wide range of control sensitivities in any specific task with little change in tracking performance. However, in terms of subjective ratings, the human does show a preference for a narrower range of control sensitivities with any controlled element and task. For example, consider Fig. 31, which shows pilot ratings versus an abscissa defined as K/K_B (K_B = "best" gain, i.e. that receiving lowest numerical pilot rating) for a variety of different controlled elements in a compensatory tracking task (McDonnell, 1968).

Unfortunately for the control system designer, the optimum control sensitivity is a function of the controlled element dynamics, and in some cases, the nature of the control task. This is demonstrated in Fig. 32, which shows the average pilot ratings as the SCAS command gain, K_c, and the aircraft's roll-mode time constant, τ_R were varied in a flight experiment (Smith, et al, 1981). The tracking tasks were gun tracking and air refueling. The numbers within the circles refer to vehicle configurations, while the numbers above the circles refer to averaged pilot ratings. The units on the command gain refer to the high-frequency gain of the vehicle transfer function between roll attitude and control force e.g., $\phi/F_s = K_c/[s(s+(1/\tau_R))]$. The force-feel system in this experiment utilized a force-sensing control stick.

Another factor entering into the selection of the optimum control sensitivity is the force-feel system "gradient", usually expressed in terms of stick force per degree or per inch of stick deflection. This gradient is equivalent to $(\omega_F)^2/K_F$ in Eq. 2. Figure 33 shows pilot rating results indicating the interdependence of the command gain and force-feel system gradient for the fixed-base tracking tasks studied by Johnston and Aponso (1988). A position sensing control stick was being utilized here. Note that here, the command gain, K_c, is defined differently than in Fig. 32 (allowing a zero time constant to be employed). Obviously, at constant control sensitivity, the force-feel system "gradient" can have a strong effect upon pilot rating, and obviously vice-versa (recall the scatter in the data of Fig. 20 being attributed to different control sensitivities).

From the brief treatment given here, it should be obvious that any discussion of the impact of force feel-systems on handling qualities *must* include a thorough documentation of all the pertinent parameters and conditions mentioned in Section 2.2, i.e. natural frequency, damping ratio, gradient, control sensitivity, and force or position sensing.

5.0 VIBRATION AND ACCELERATION ENVIRONMENTS

While not a handling qualities topic, *per se*, vibration, acceleration and the effects of flexible vehicle modes can adversely effect vehicle handling and performance. One manner in which this can occur is by interference through biodynamic interfaces such as the force-feel system. Figure 34 shows the various biodynamic interfaces for manual control (Jex, 1971). The dashed lines in this figure represent biodynamic interference. As can be seen, the control interface is affected by control/floor coupling (i.e. with no human intervention) and by induced control forces.

One of the simplest types of biodynamic interference phenomena is the "limb-bobweight" effect, e.g. the pilot's hand/arm acting like an in inert mass atop the control stick. Hess (1990b) offered one simple approach to modeling this phenomenon, with switch 1 closed in Fig. 12. The block with transfer function $rm_e s^2$ is a rudimentary model of biodynamic feedback. It represents that component of the "inertia force" in the direction of the pilot's applied force δ_F, which would be imparted to the manipulator when the vehicle undergoes an angular acceleration, e.g. roll acceleration. Here, r represents the distance of a manipulator-limb point mass, m_e, from the vehicle roll axis. The radius r is considered positive, if in the condition of normal wings-level flight, the effective point mass is above or below *both* the vehicle instantaneous roll axis and the rotational axis of the manipulator. Only positive r values were considered by Hess.

The last four rows of Table 3 show the pilot model and force-feel characteristics for a hypothetical biodynamic interference analysis. Figures 35 and 36 are Bode plots for the closed-loop roll tracking system for the position and force sensing feel system of Table 3. Note that, for the vehicle dynamics considered, the magnitude peaks of these transfer functions caused by biodynamic feedback can be ameliorated by the pilot employing a tighter position control loop (larger G_l in Fig. 12). Note that in this last modeling effort, no other motion cues were considered, i.e. $K_m = 0$.

The simple model just discussed is a very rudimentary approach to modeling one biodynamic interference effect. In a much more ambitious program, Allen, et al (1973) conducted a series of experiments investigating the influence of sinusoidal vibration (vertical, lateral, fore and aft) on manual control performance. Human operator transfer functions and remnant were measured. It was found that there were two important effects of vibration on the human operator's transfer function. The first was that control motions were dominated by the vibration, itself. That is, a significant portion of the controller output was linearly correlated with the vibration input. A second effect was that there was a significant increase in the human operator remnant, i.e. that portion of the human operator's output that was uncorrelated with either the command input or the vibration. Figure 37 shows the biomechanical model which was developed to explain the experimental results.

A more complete model for vibration effects in terms of human sensing and actuation is shown in Fig. 38 (Reidel, et al, 1980). This model of the semi-supine pilot includes effects that can occur through visual sensing in a vibrating environment. The physical model uses an isomorphic, lumped-parameter approach to represent the dominant whole-body joints and resulting modes of motion.

As an example of vibration and motion effects due to vehicle flexibility, consider a flexible aircraft with a pitch rate command SCAS (e.g., Chan, et al, 1992). One of the primary components of vibration feedthrough derives from normal acceleration at the pilot's station, n_{zp}. A biodynamic analysis of this flight control problem might begin with Fig. 39. Here the block labeled "pilot/stick dynamics" represents the dynamics of the model of Fig. 38. Figure 40, taken from Allen, et al, (1973), shows the transmissibility of the human for vertical vibration, with the symbols representing measurements and the solid lines representing results from a parameter estimation study using the model of Fig. 38. This data was taken with a center stick with a very stiff spring restraint. This model and the dynamics of the command path filter, q_c/f_s and the vehicle, n_{zp}/q_c, can be used to ascertain closed-loop stability in a vibrating environment and also to design force-feel system filters to improve damping. The study of Chan, et al, (1992) gives a nice example of such a design for a flexible vehicle representing a hypersonic aircraft.

An interesting example of the deleterious effects of a vibrating environment is provided by Glusman, et al (1986) in discussing flight tests of the U.S. Army's Advanced Digital Optical Control System (ADOCS) rotorcraft. This vehicle possessed a very limited motion ($\pm$ 0.156 inches) force-sensing collective side-stick controller, sketched in Fig. 42. The gradient for this controller was 95.6 lbf/in (up) and 85 lb/in (down). In certain flight maneuvers where constant collective force was required and vehicle structural vibration levels were high, a biomechanical feedthrough occurred, and an inadvertent 6.5 Hz control input resulted. A time history of one such occurrence is shown in Fig. 41. The solution to this problem was the implementation of a notch filter on all stick outputs. As in many implementations of force sensing control sticks, low-pass filtering of control stick outputs was also implemented. It is interesting to note that the combined effective delay of the low-pass and notch filters in the pitch channel was approximately 70 ms, which accounted for approximately 30% of the total effective delay in that channel (Tischler, et al, 1991).

The effects of high-acceleration environments, such as "high-g" maneuvering in combat aircraft is of concern in the design of force-feel systems. As an example, Repperger and Frazier (1983), discuss the design of what they refer to as a "smart stick" to aid the pilot operating in a high-g environment. Here the smart stick refers to hand controllers with computer-adjustable equivalent mass, spring constant and damping and designed to operate in the acceleration environment. Figure 42 is a diagrammatic representation of the problem considered. The pilot is illustrated as a biomechanical model, similar to that discussed by Reidel (1980). An acceleration field is sensed via accelerometers and an onboard computer adjusts the stick parameters B_s, M_s, and K_s. The authors distinguish between "positive" and "negative" biomechanical feedthrough in acceleration environments. For example, if a stick movement made in the $+y$ direction (where y can be considered as an aircraft-fixed axis direction) gives rise to an inertial force, G_y, in the $+y$ ($-y$) direction, then positive (negative) biomechanical feedthrough occurs. Recall here that an inertial force is defined as $-m_e a_y$, where m_e is some equivalent mass, and a_y is the acceleration in the y direction. The authors point out that positive biomechanical feedthrough is comparable to positive feedback in a control system, and can therefore be destabilizing.

The authors consider a number of design options for the smart stick. In particular, they consider creating a negative biomechanical feedthrough design, wherein the computer adjusts the variables B_s, K_s, and M_s in Fig. 42 such that an effective negative biomechanical feedthrough is always created. In a later paper, Repperger, et al, (1984) discuss the hardware and construction of such a stick, and demonstrate its performance in an acceleration environment. In a series of compensatory tracking tasks, root-mean-square error scores with the smart stick were a factor of 2-3 smaller than those for a passive stick in the same acceleration environment. It should be noted that stick position was the command variable

throughout these studies.

A technique for electronically compensating for the effects of a vibrating environment in manual control tasks is presented by Velger, et al, (1984). The authors distinguish between two cases of biodynamic interference, (1) biodynamic open-loop, in which the interference is not related to the voluntary control activity of the operator, e.g. manipulations of weapons or sights, and (2) biodynamic closed-loop, in which the interference is due to vehicle motion induced by operator commands. Focusing upon the latter case, Fig. 43 shows the adaptive filtering scheme the authors employed in a computer simulation of a high-performance aircraft. The success of this approach using a least-mean-square (LMS) filter depends upon the a separation of the spectral content between the voluntary pilot commands and the involuntary biodynamic disturbances. The authors demonstrate the utility of their scheme in a computer simulation of the piloted longitudinal control of the YF-12 aircraft, with a body bending mode included in the vehicle model. The pilot model in the simulation was a simple gain. The LMS filter was able to eliminate PIO's without essentially impairing the dynamics of the pilot-vehicle system.

In a related study, Velger et al (1988) again employed the LMS filtering scheme in a human-in-the loop moving-base simulation study. The simulator motion forcing function was filtered white noise in roll and pitch. In this study, pilot control commands did not affect the motion of the simulator. Thus, this study is an example of biodynamic open-loop interference, as just described. However, in this experiment there was no spectral separation between voluntary pilot motion and involuntary biodynamic disturbances. The hand controller in this study was a two-axis F-16 sidestick (force sensing). The authors demonstrate that, relative to the static (no motion) case, biodynamic interference caused a significant degradation in tracking performance, a decrease in the pilot's control "gain" and an increase in effective time delay. With the LMS filter, the RMS value of the tracking error was, on the average, a factor of 2 smaller than that obtained without the filter.

6.0 NONLINEARITIES

All irreversible, fly-by-wire flight control systems will entail the deliberate introduction of nonlinearities in the force-feel system (e.g. Black and Moorhouse, 1979; Citurs, 1984). Force-displacement detents are typical examples of such nonlinearities. Of course, even in fly-by-wire systems, any purely mechanical elements in the force-feel system will almost invariably introduce small nonlinearities such as hysteresis and friction. In addition, most SCAS designs will include a nonlinear command gradient, a typical example of which is shown in Fig. 44 for roll control (here assuming a force-sensing force-feel system and a roll-rate command SCAS). A major reason for the nonlinear gradient is to reduce sensitivity for small roll-rate commands and provide adequate roll performance for large roll-rate commands (Hoh, et al, 1982).

It is interesting to qualitatively analyze the effect a nonlinearity such as detent in the framework provided by the pilot models which have been discussed in the preceding. For example, the effects of nonlinearities in the force-displacement characteristics for movable controllers, or the force-electrical output characteristics in force controllers will depend upon the command variable being employed, i.e. force or position. In movable controllers involving position sensing or command, a nonlinearity such as detent force-displacement nonlinearity will appear in the *forward* loop of a representation of the pilot such as Figs. 10 or 12. The effect of this detent (or of any nonlinearity in this particular location) on pilot/vehicle performance will be mitigated considerably by the ability of the pilot to close a high-gain displacement loop around the manipulator. However, In the case of movable controllers involving force command or sensing, a detent force-displacement nonlinearity will appear in the *feedback* loop of the pilot representations of Figs. 10 or 12. Assuming the validity of these pilot models, this latter implementation might produce serious performance problems, since a high gain displacement loop around the manipulator will now amplify the effect of this nonlinearity. In the case of an isometric controller with a force-electrical output detent, the nonlinearity would now be outside the proprioceptive (force) feedback loop and would be expected to have a larger effect upon pilot/vehicle performance than would be the case for moving controller involving displacement sensing or command.

There has been little research upon the effects of nonlinearities like those just discussed in terms of measured pilot/vehicle performance, transfer functions and pilot opinion. The work of Wasicko and Magdaleno (1965) and Graham (1967) mentioned in Section 2.1 provide notable exceptions. It is interesting to refer to one experiment by Graham (Ibid) which involved compensatory tracking with control friction. Figure 45 taken from the AMRL report shows the pilot/vehicle system (note the question mark concerning proprioceptive feedback!). Figure 46 demonstrates the amount of hysteresis which could be generated by varying the tension in control cables in the experimental facility. To put the magnitude of this hysteresis in perspective, the stick spring restraint for the tracking experiment was 0.6 lbf/deg. The feel spring was disconnected in generating this figure and the maximum friction force was 10 lbf., here. In terms of the discussion of the previous paragraph, this force-feel system was a movable, position-sensing device. Thus, the hysteresis nonlinearity was in the forward loop of the pilot's proprioceptive feedback structure. A necessary condition for the conclusions of the *gedanken* experiment of the previous paragraph to be correct would be little evidence of deterioration in tracking performance with friction. Figure 47 corroborates this conclusion, since little change in normalized mean-square tracking error is seen to occur as friction level is varied.

7.0 SUMMARY AND FUTURE DIRECTIONS

The preceding sections have attempted to highlight the research efforts which have surrounded the development of aircraft force-feel systems, with particular emphasis upon irreversible, fly-by-wire implementations. Unfortunately, scant attention has been paid to providing *design* guidelines. The reason for this apparent oversight is simply that sufficient ambiguity exists in the literature to make any but very general recommendations suspect. The issue of including or excluding force-feel system dynamics in aircraft/rotorcraft handling qualities assessment is a case in point. Thus, the author has adopted the approach of summarizing pertinent research efforts in an effort to apprise the reader of the state of the art in force-feel system analysis and design.

It would appear that those research efforts which have made significant inroads into the design issues surrounding force-feel systems have done so through a combination of the analytical and the experimental. The importance of adopting a closed-loop perspective in both these approaches cannot be overemphasized. Recent history has made one thing painfully evident: With the increasing performance capabilities of modern aircraft/rotorcraft, the information processing and actuation limitations of the human pilot play even more critical roles in the overall success and safety of these vehicles than in the past. This is somewhat surprising since "conventional wisdom" has suggested that the human pilot is being supplanted by the computer, thus freeing the former for a lower-workload supervisory role in the cockpit, and by inference, a less pivotal role in mission success. This view has not been borne out in practice. The depressing regularity with which modern aircraft, from fighters to transports, have exhibited a susceptibility to pilot induced oscillations provides a highly visible counter-example (McKay, 1994).

It is probably unrealistic to assume that additional significant research resources will be directed toward the problems of force-feel system design in the foreseeable future, despite the lack of consensus on important issues outlined in the latter sections of this monograph. As often in the past, shortcomings in these systems will be overcome by the adaptive human pilot, and where this is not possible, the systems will be subject to *a-posteriori, ad-hoc* modifications and improvements. Perhaps part of this problem is the difficulty in convincing the flight control system engineer that his/her highly responsive, high-bandwidth, robust flight control system may be seriously compromised by the characteristics of the cockpit manipulator and by the (sometimes) unchartered limitations of the human pilot who is using it. Nonetheless, it is hoped that the design approaches and research outlined herein, may contribute to a better understanding and appreciation of the importance of force-feel system design in aircraft/rotorcraft flight control.

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Table 1 Manipulator feel system types in the model of Fig. 12 (Hess, 1990b)

Manipulator	Y_{FS}	Switch 2 position
Free-moving	$1/s^2$	down (δ_M = displacement)
Pressure	1.0	up (δ_M = force)
Feel system force sensing	$\dfrac{1}{(s/\omega_F)^2 + 2\zeta_F s/\omega_F + 1}$	up (δ_M = displacement)
Feel system displacement sensing	$\dfrac{1}{(s/\omega_F)^2 + 2\zeta_F s/\omega_F + 1}$	down (δ_M = displacement)

Table 2 Dynamic requirements for force-feel systems in MIL-STD-1797A (Mitchell, et al, 1994).

REQUIREMENT	APPLICATION OF REQUIREMENT	INCLUDE OR EXCLUDE FEEL SYSTEM?
4.2.1.2 Short term pitch response	**A. CAP or $\omega^2_{sp}/(n/\alpha)$, ζ_{sp}:** "requirements apply to the equivalent-system parameters determined from the best match for force inputs, and also for deflection inputs" **Equivalent pitch time delay, τ_θ:** "apply to the value for $\theta(s)/\delta_{es}(s)$ for a deflection control system... and to $\theta(s)/F_{es}(s)$ for a force control system"	**BOTH** **EXCLUDE**
	B. $\omega_{sp}T_{\theta_2}$, ζ_{sp}, τ_θ: Same as above	**BOTH**
	C. Transient peak ratio, rise time: "response to a step input of pitch controller force, and also to a step controller deflection" **Effective delay:** "step controller deflection for a deflection control system... and the step controller force for a force control system"	**BOTH** **EXCLUDE**
	D. Bandwidth, Time Delay: "response to pilot control force for force controllers... and to pilot controller deflection for deflection controllers"	**EXCLUDE**
	E. Closed-Loop Criterion [Neal-Smith]: "The pilot output is force for force controllers... and deflection for deflection controllers"	**EXCLUDE**
	F. Time- and frequency-response criteria by Gibson: Not stated either way (some figures show force, some show deflection)	**UNKNOWN**
4.5.1.1 Roll mode	"Use δ for deflection control systems... and F for force control systems"	**EXCLUDE**
4.5.1.5 Roll time delay	Obtain equivalent time delay from applying 4.5.1.1	**EXCLUDE**
4.6.1.1 Dynamic lateral-directional response	"Use δ_{as} for deflection controls... and F_{as} for force controls"	**EXCLUDE**

Table 3 Pilot model and force-feel system parameters (Hess, 1990b).

Neuromuscular System	Manipulator–Feel System	Sensing	Vehicle (Y_c)	G_1	K_e	τ_0 (sec)	K_m	m_e
$\frac{e^{-0.05s}}{(s/20)^2+2(0.7)s/20+1}$	$\frac{1}{(s/14)^2+2(0.7)s/14+1}$	Position	$1/[s(0.15s+1)]$	1.0	6.25	0.05	0	0
↓	↓	Force	↓	↓	6.25	↓	↓	↓
↓	↓	Position	↓	↓	7.14	↓	0.4	↓
↓	↓	Force	↓	↓	7.14	↓	0.4	↓
↓	↓	Position	↓	↓	8.0	↓	0	0.5
↓	↓	Position	↓	4.0	16.0	↓	↓	↓
↓	↓	Force	↓	1.0	8.0	↓	↓	↓
↓	↓	Force	↓	3.5	14.5	↓	↓	↓

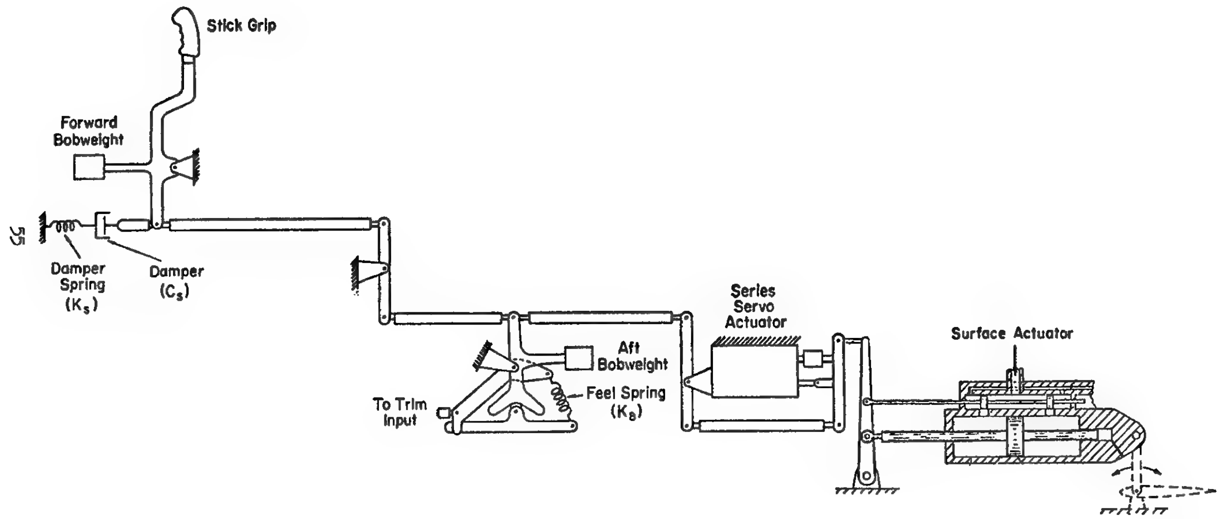


Fig. 1 A mechanical force-feel system (McRuer and Johnston, 1975).

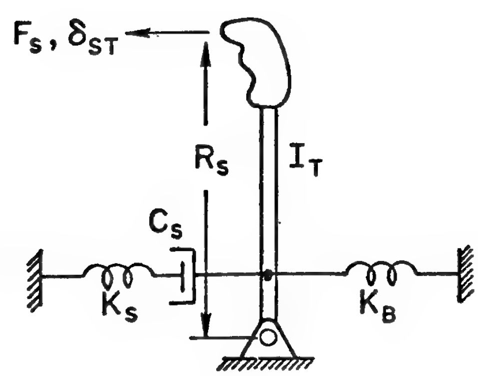


Fig. 2 A linearized model of the system of Fig. 1 (McRuer and Johnston, 1975).

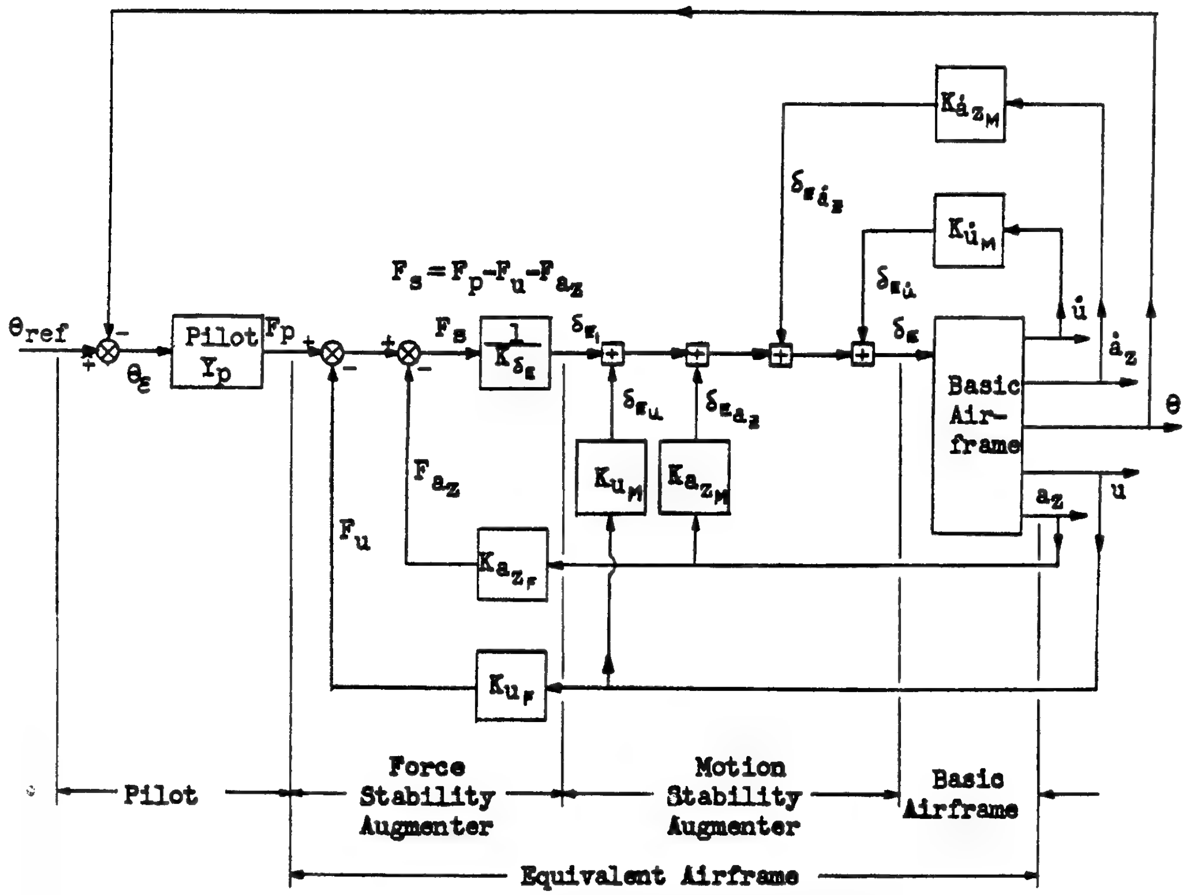


Figure III-16. Generalized Block Diagram of Pilot-Equivalent Airframe System

Fig. 3 A generalized block diagram of pilot-equivalent airframe system (Anon, 1953).

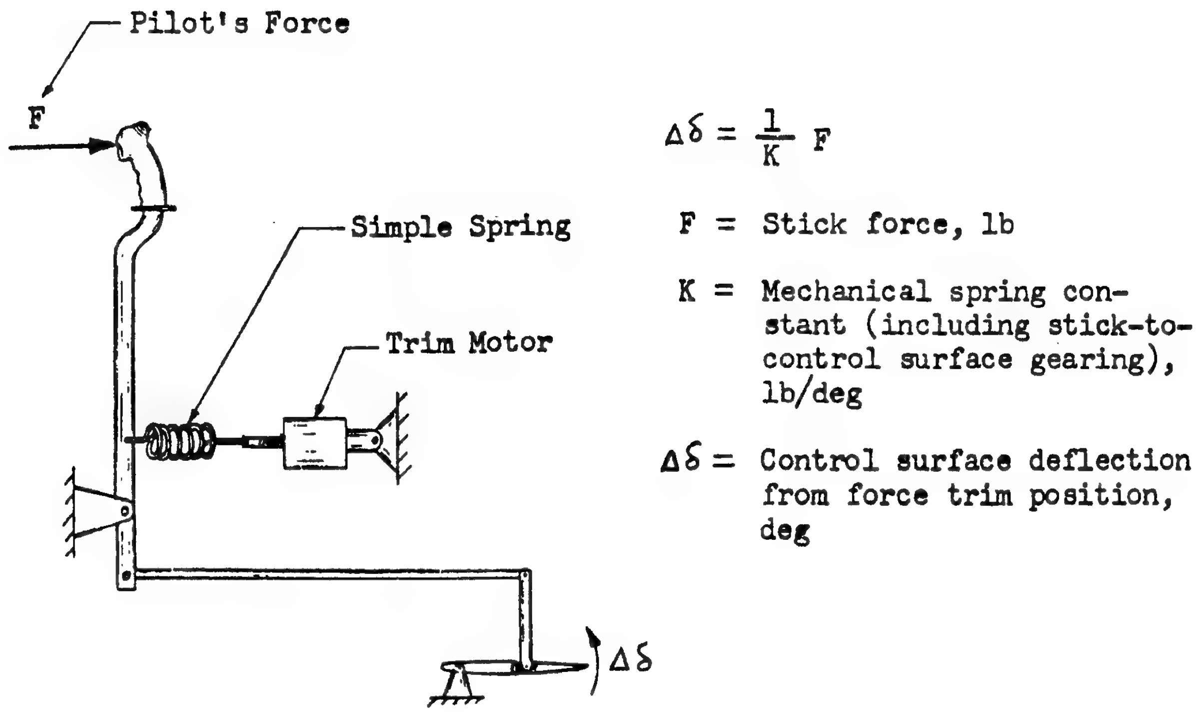


Fig. 4 Simplified force-feel system for diagram of Fig. 3 (Anon, 1953).

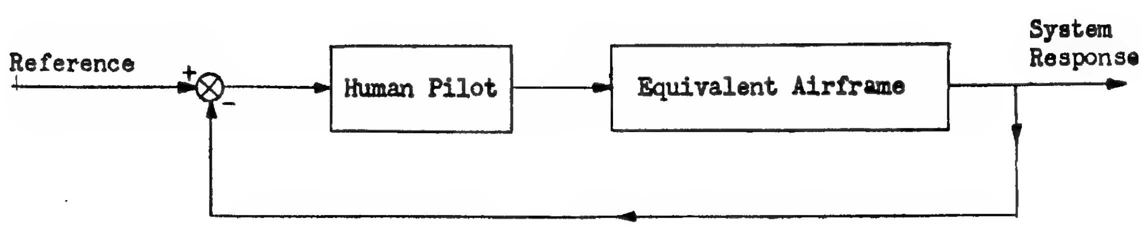


Fig. 5 Simplified version of Fig. 3 (anon, 1953).

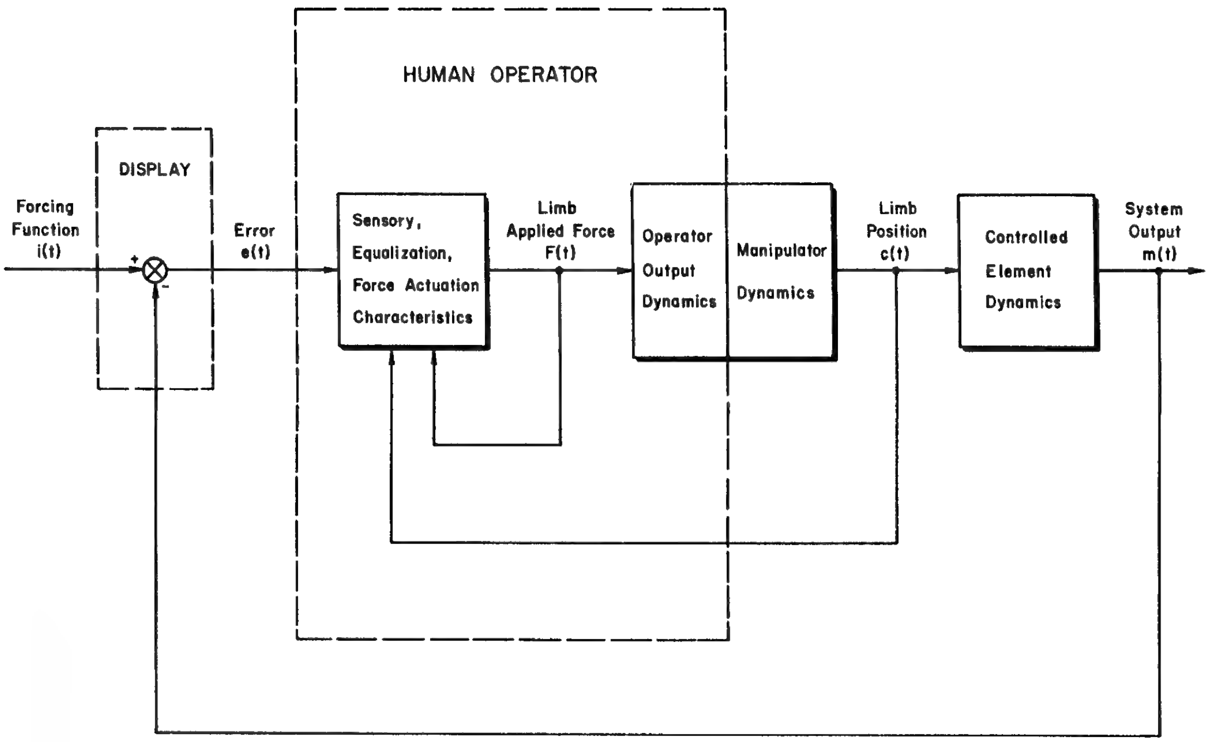


Fig. 6 Representation of single-loop manual control system (McRuer, et al, 1965).

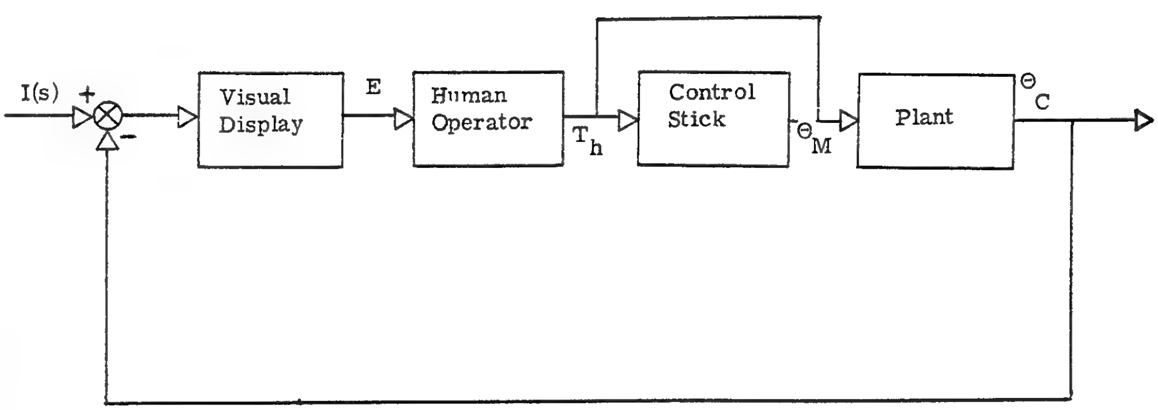


Fig. 7 The "matched manipulator" control system (Herzog, 1969).

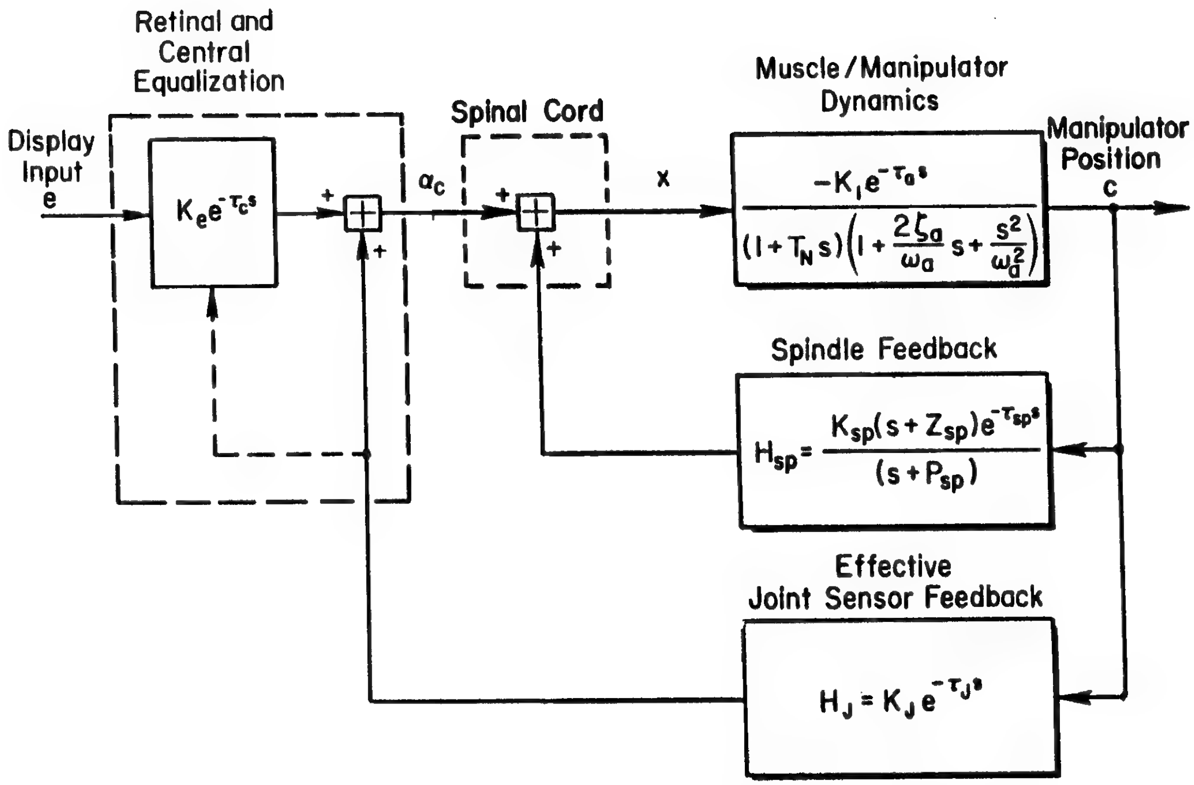


Fig. 8 Neuromuscular subsystems for free-moving and pressure manipulators, and central equalization for rate dynamics (McRuer and Magdaleno, 1971).

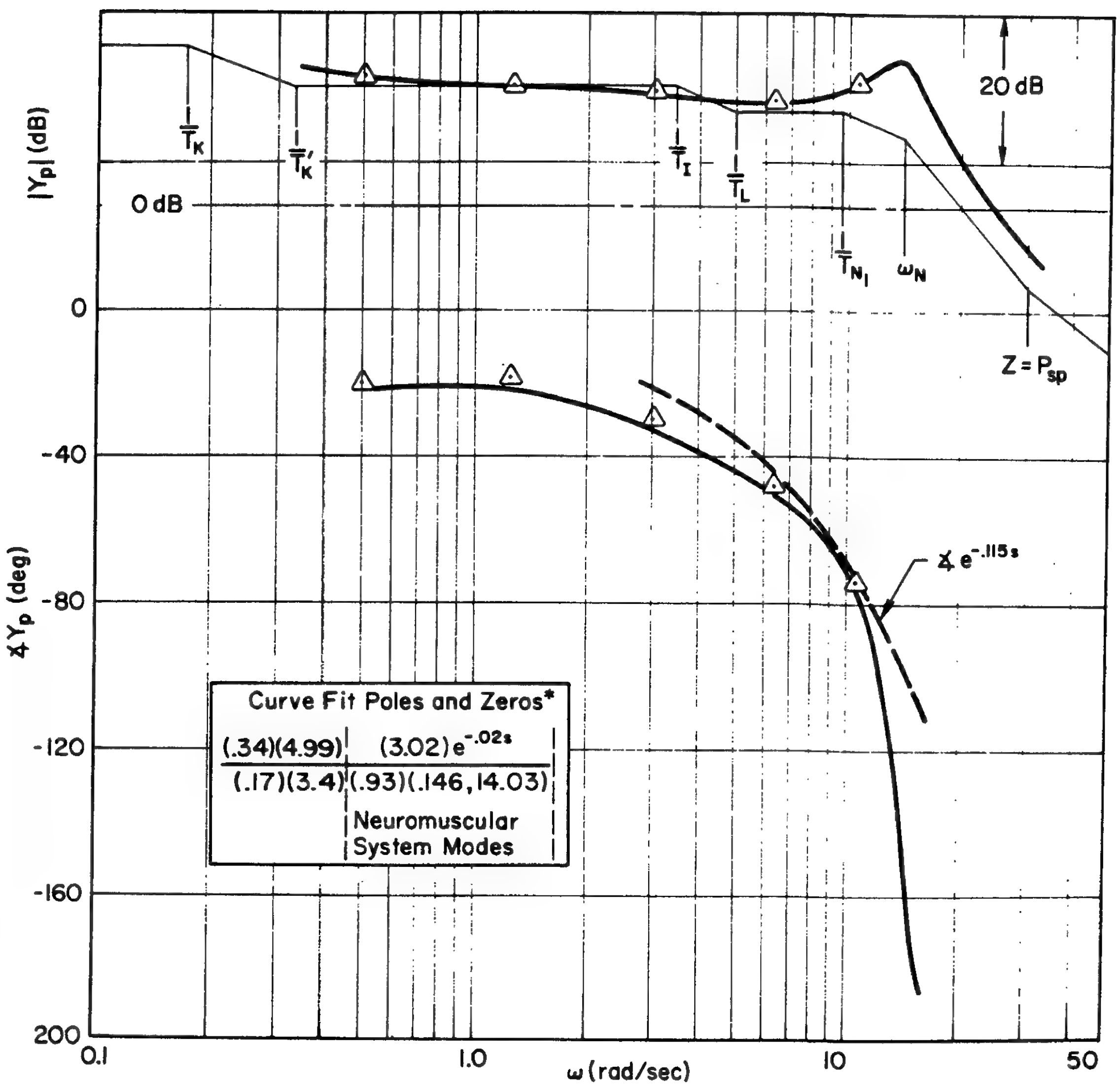


Fig. 9 Measured Y_p for hand manipulator and controlled element dynamics Yc = 1/(s−1) (McRuer and Magdaleno, 1971).

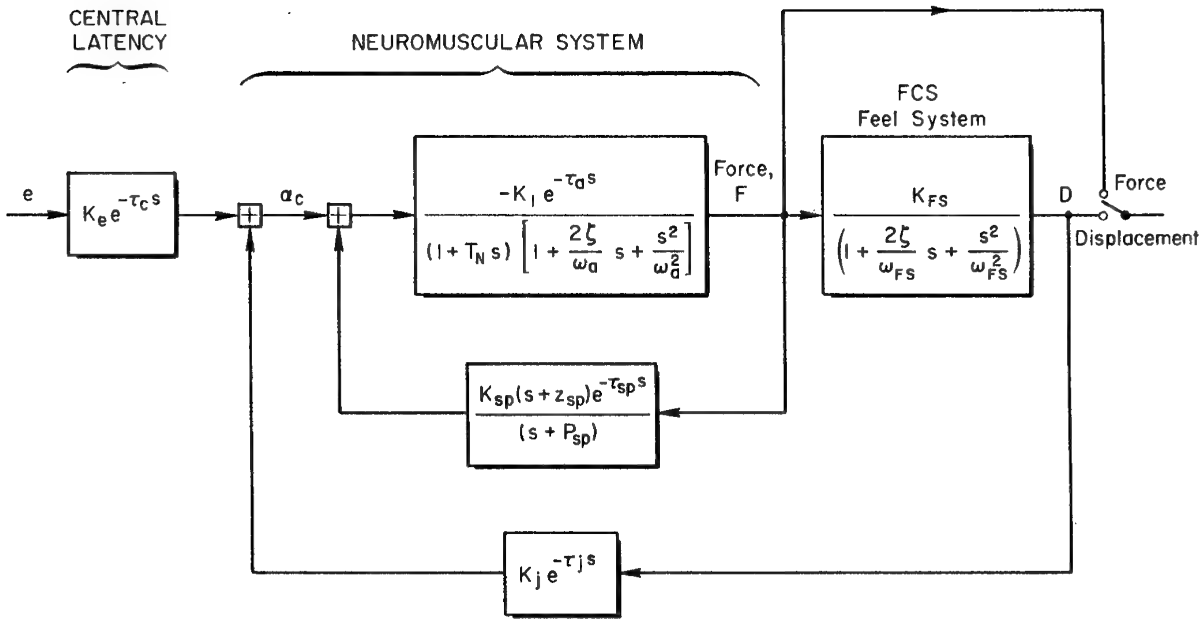


Fig. 10 Neuromuscular subsystems for general force-feel systems, with force or position sensing and central equalization for rate dynamics (Johnston and Aponso, 1988).

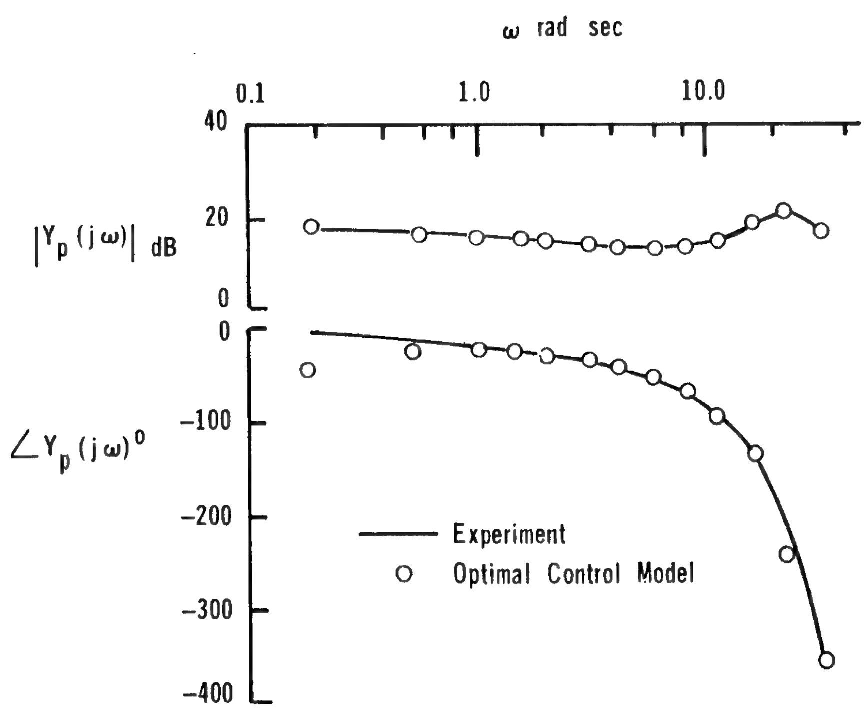


Fig. 11 Bode plot of human operator transfer function obtained from optimal control model (Hess, 1987).

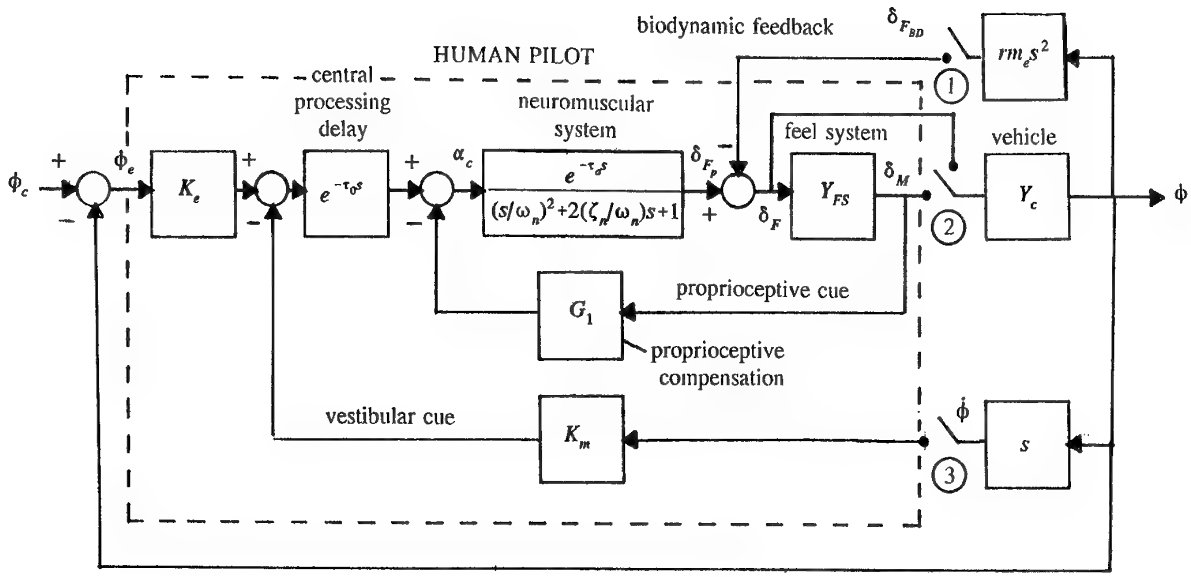
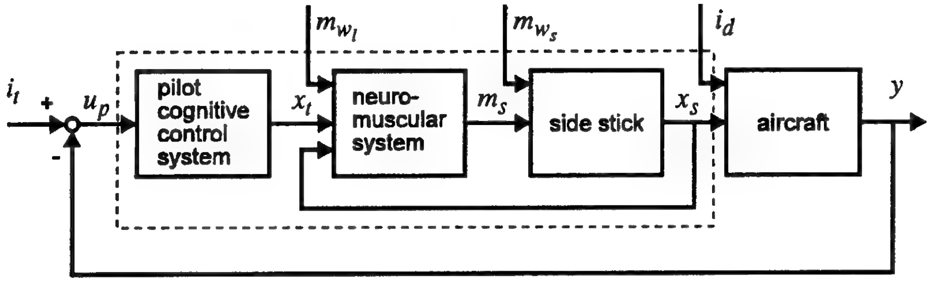
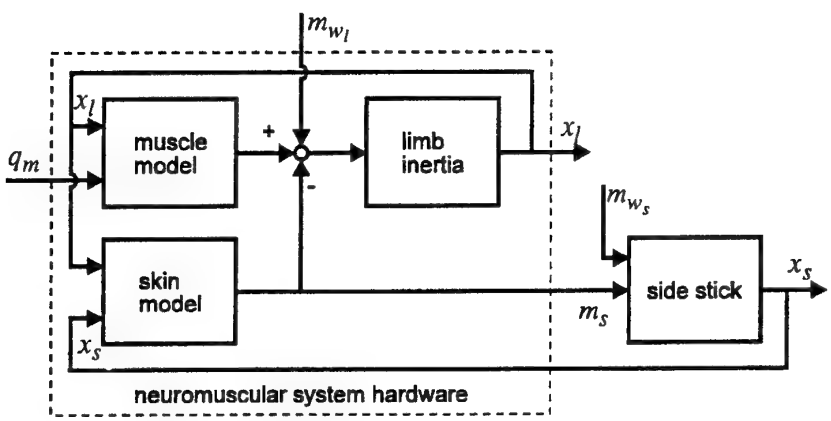


Fig. 12 The structural model of the human pilot (Hess, 1990b).



The model of the neuromuscular system in a closed loop control situation, in combination with the pilot's cognitive control system, the side stick and the aircraft. The inputs of the model of the neuromuscular system are the target position, x_t, and the side stick position, x_s. The output of the neuromuscular is the moment exerted on the side stick, x_s. The noises m_{w_l} and m_{w_s} represent external moments on the limb and stick. i_t is a target signal and i_d represents a disturbance on the aircraft. Other signals are the pilot's visual input u_p and the aircraft output y.

Fig. 13 van Paassen's model of the pilot-vehicle system (van Paassen, 1994).



Hardware components of the neuromuscular system model: the muscle model, the skin model and the limb inertia model. The inputs of the neuromuscular system hardware are the stick position, x_s, and the muscle activation, q_m. The output is the moment on the side stick, m_s. In combination with the side stick, the neuromuscular system hardware can be considered to be the plant that must be controlled. The input of the plant is the muscle activation, the output is the side stick position, x_s.

Fig. 14 Sub-models included in the neuromuscular system model of Fig. 13 (van Paassen, 1994).

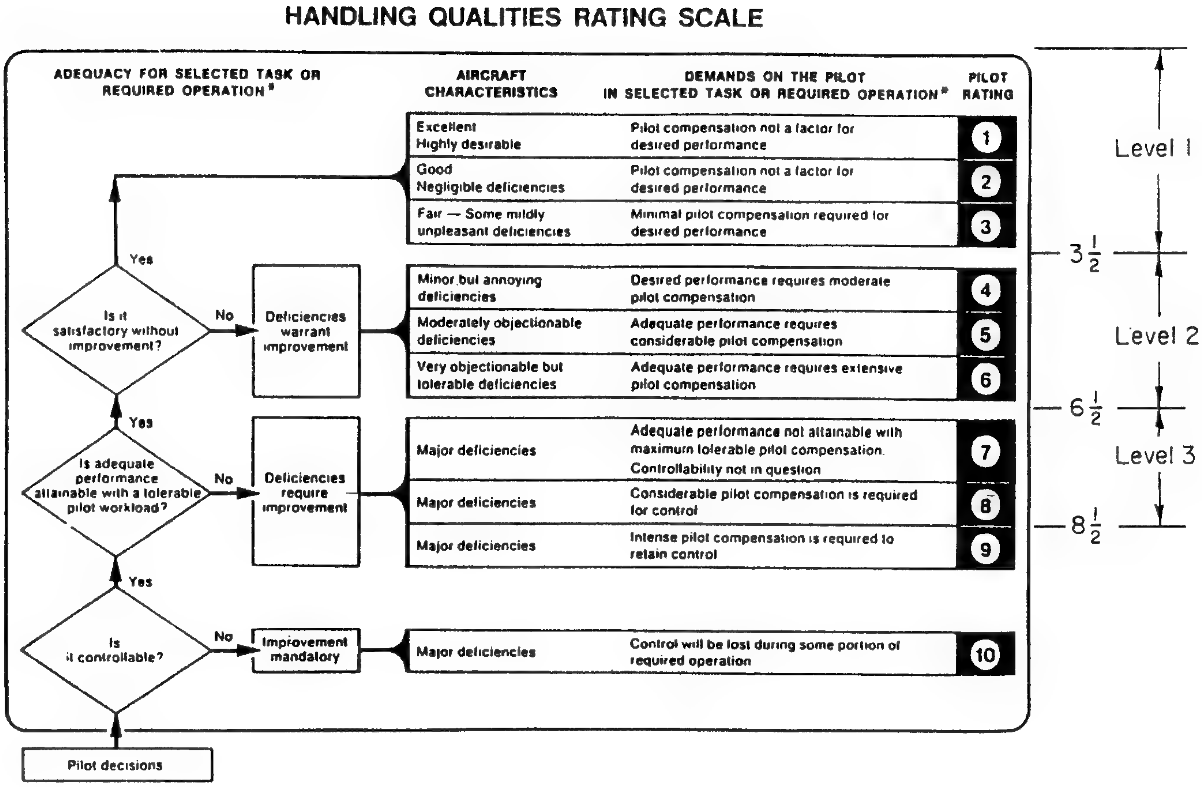


Fig. 15 The Cooper–Harper handling qualities rating scale.

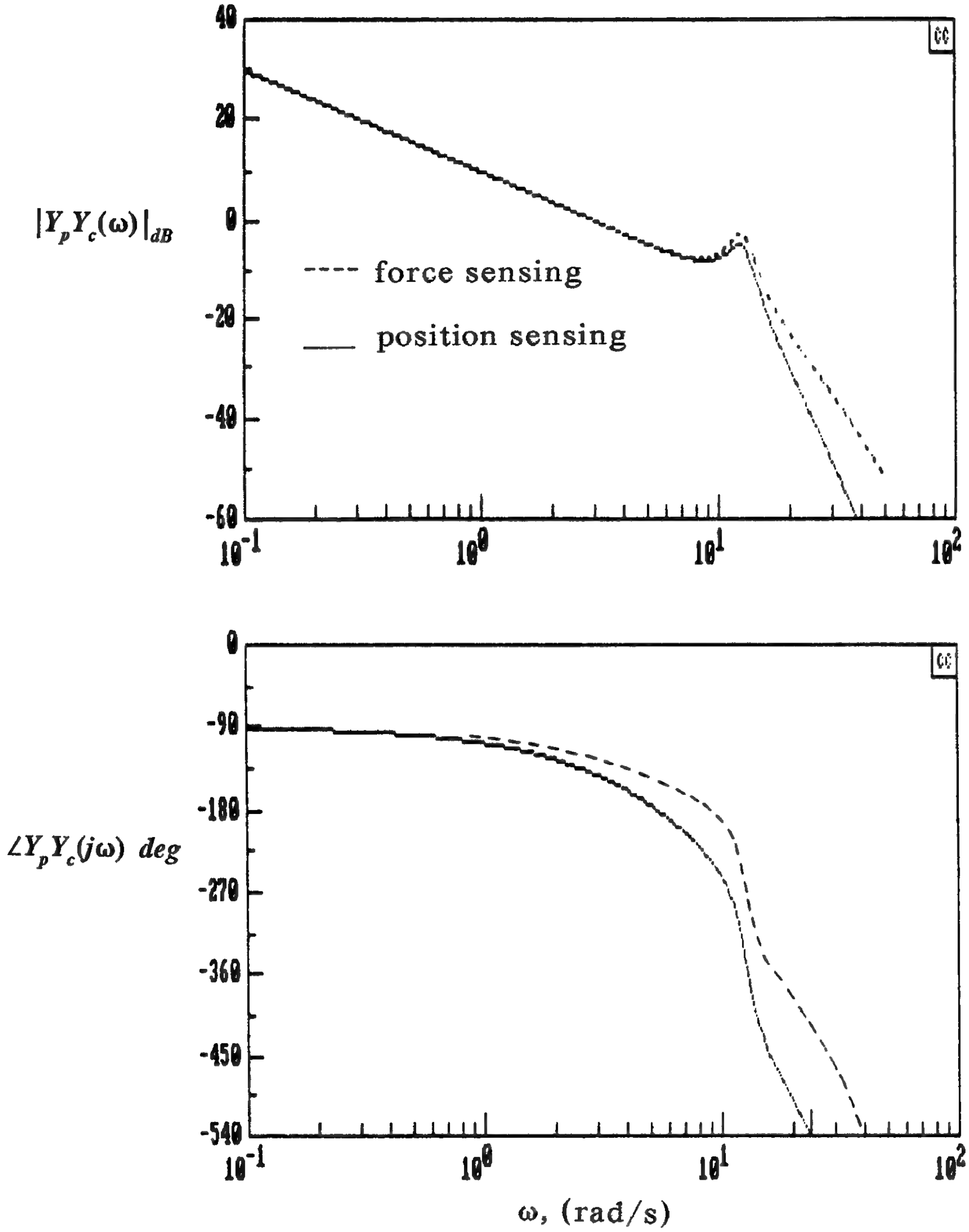


Fig. 16 Bode plots of pilot-vehicle transfer functions obtained from model of Fig. 12, position and force command (sensing) systems (Hess, 1992b).

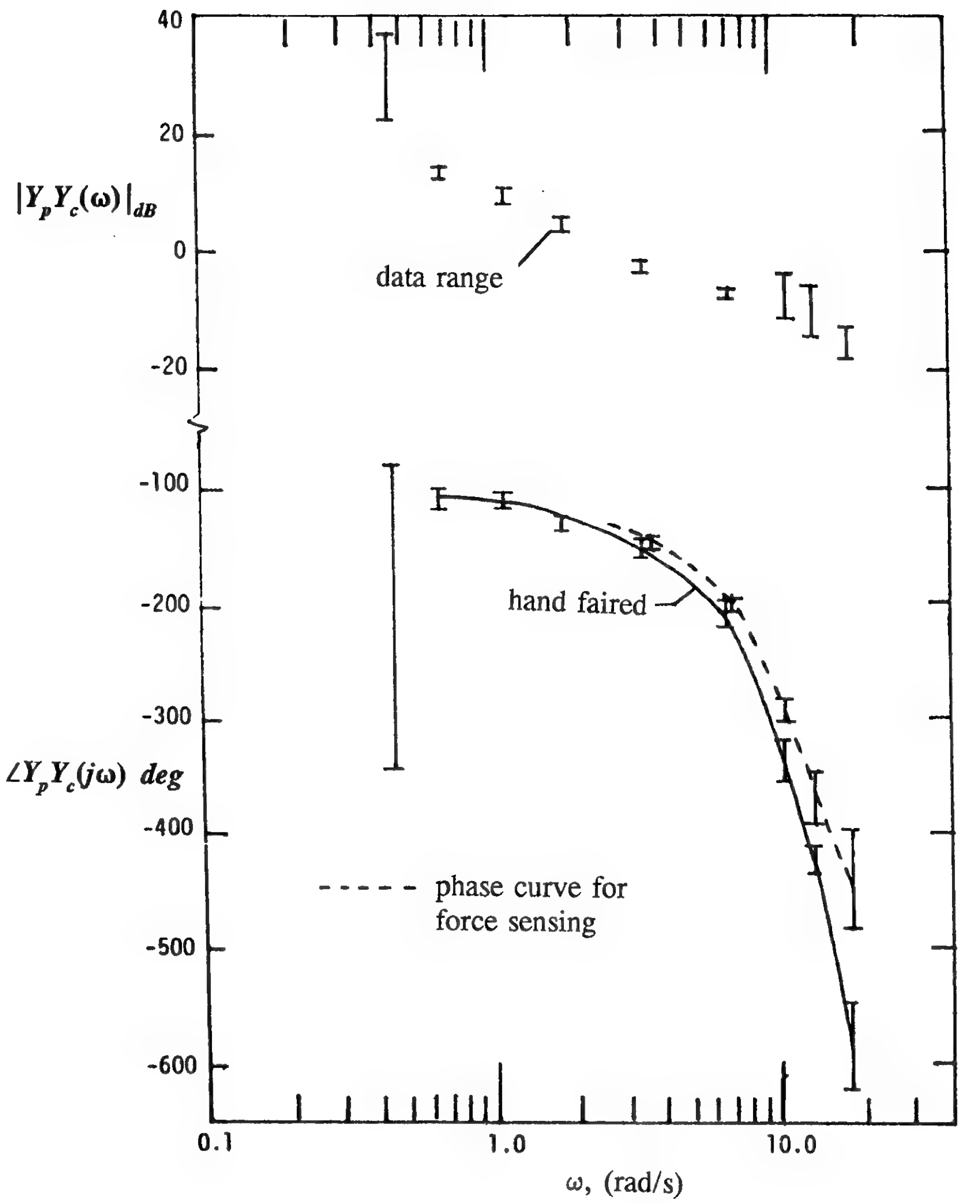


Fig. 17 Bode plot of measured pilot-vehicle transfer functions for position command force-feel system (Johnston and Aponso, 1988).

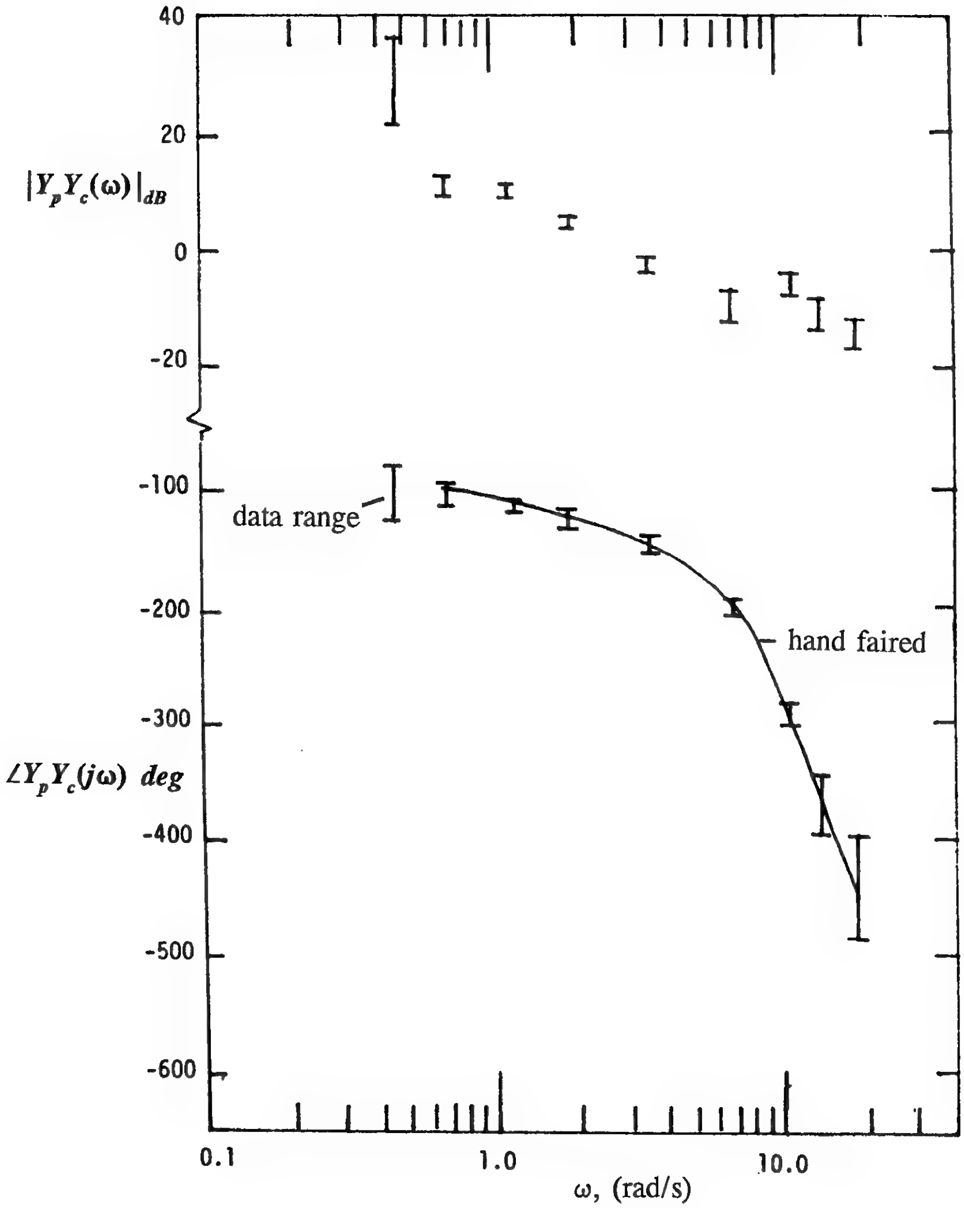


Fig. 18 Bode plot of measured pilot transfer functions for force command force-feel system (Johnston and Aponso, 1988).

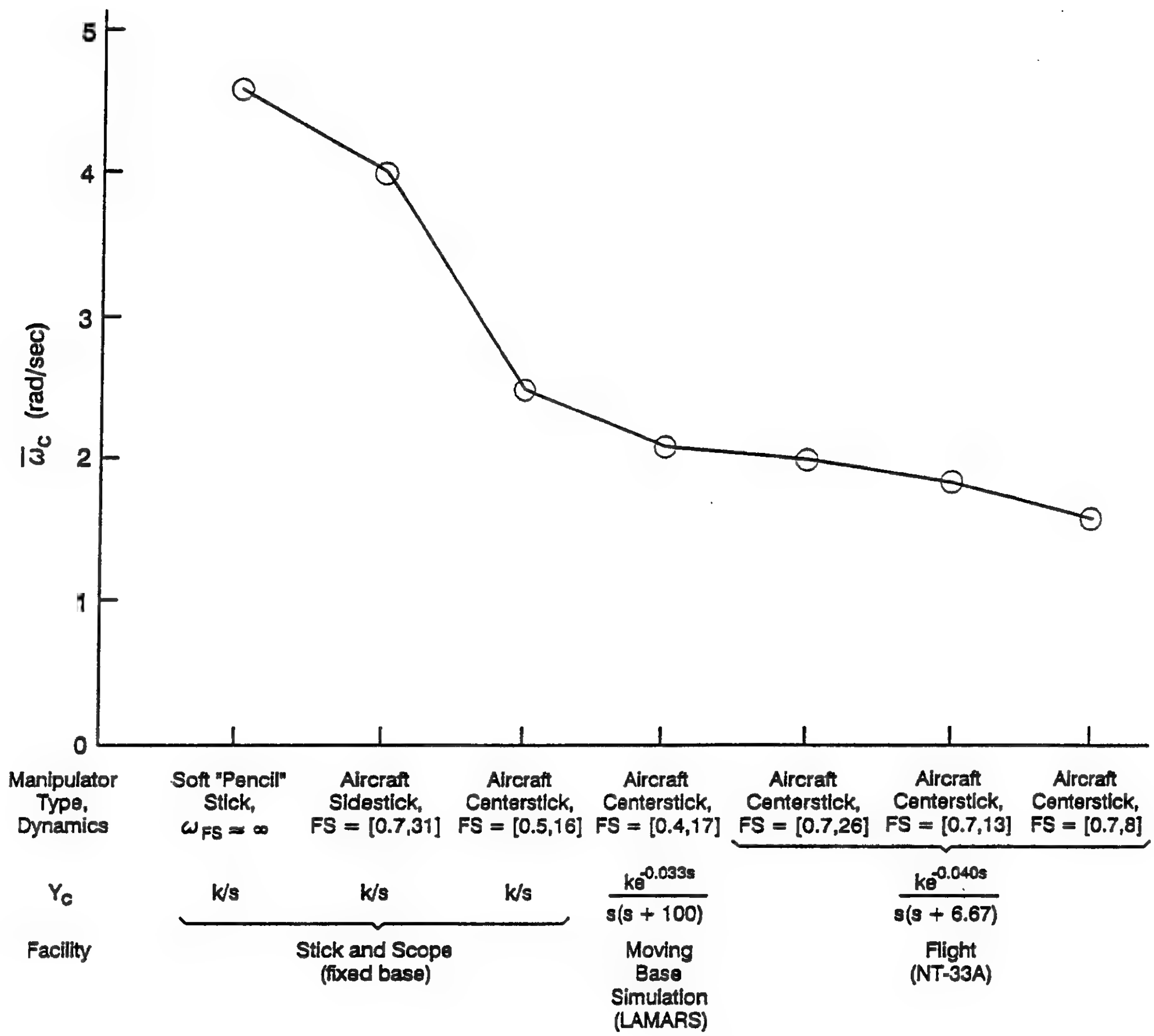


Fig. 19 Effect of manipulator and facility upon crossover frequency for roll tracking with K/s-like vehicle dynamics (Mitchell, et al, 1994).

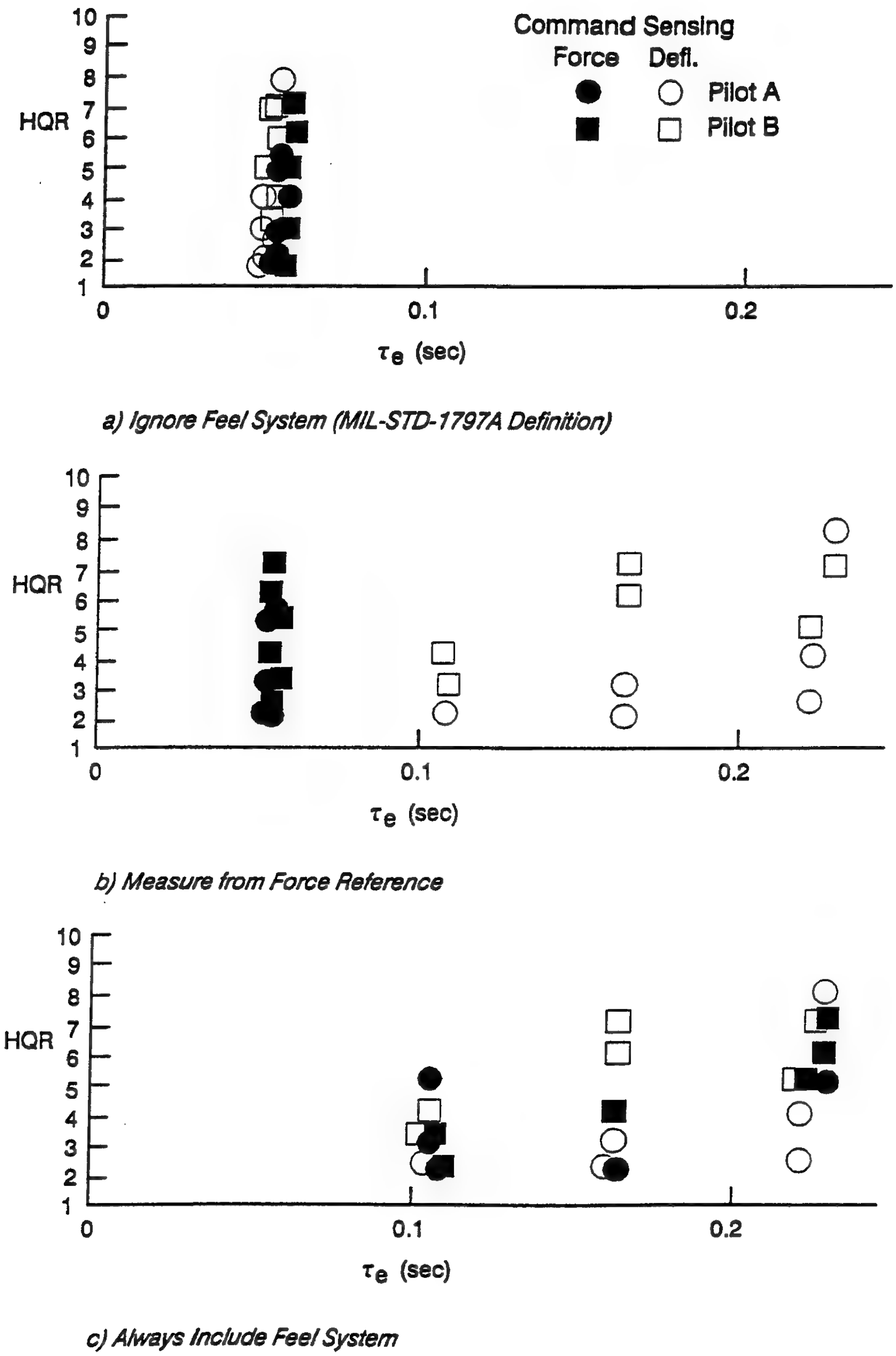


Fig. 20 Effects of force-feel system natural frequency (reflected in equivalent time delay) (Mitchell, et al, 1994).

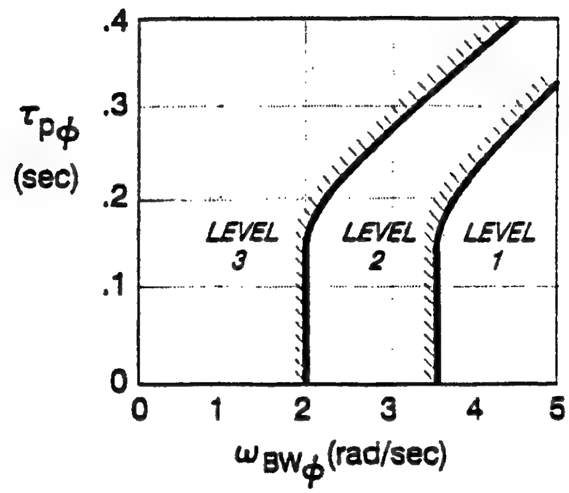


Fig. 21 Typical bandwidth-phase delay criteria for rotorcraft handling qualities (Anon., 1989).

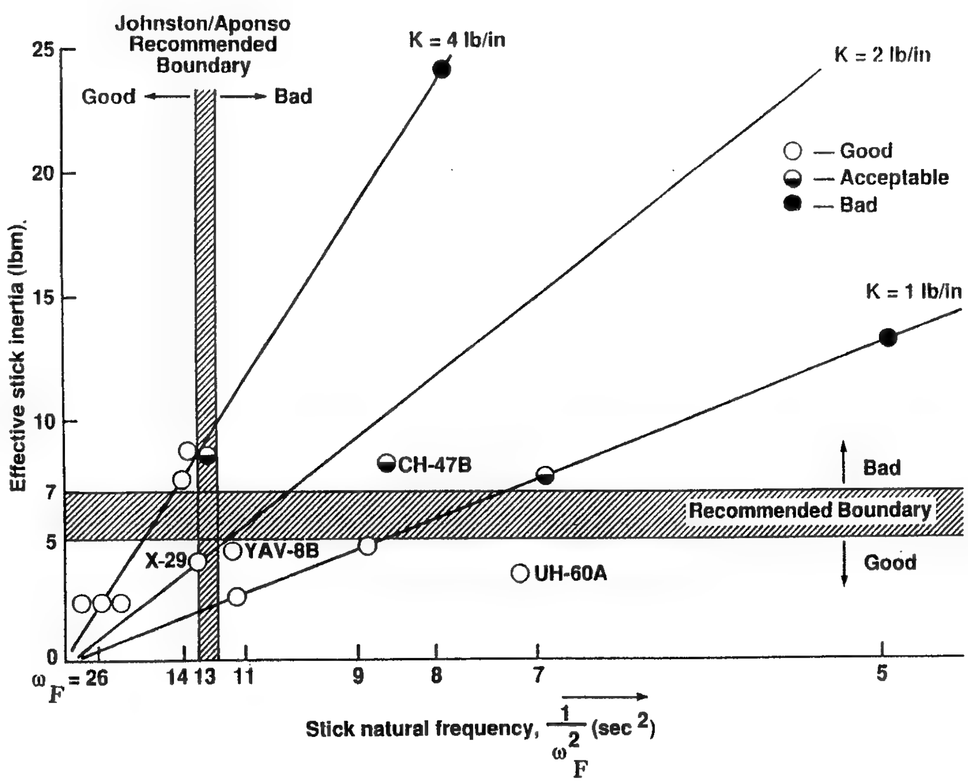


Fig. 22 Comparison of Watson-Schroeder and Johnston-Aponso boundaries.

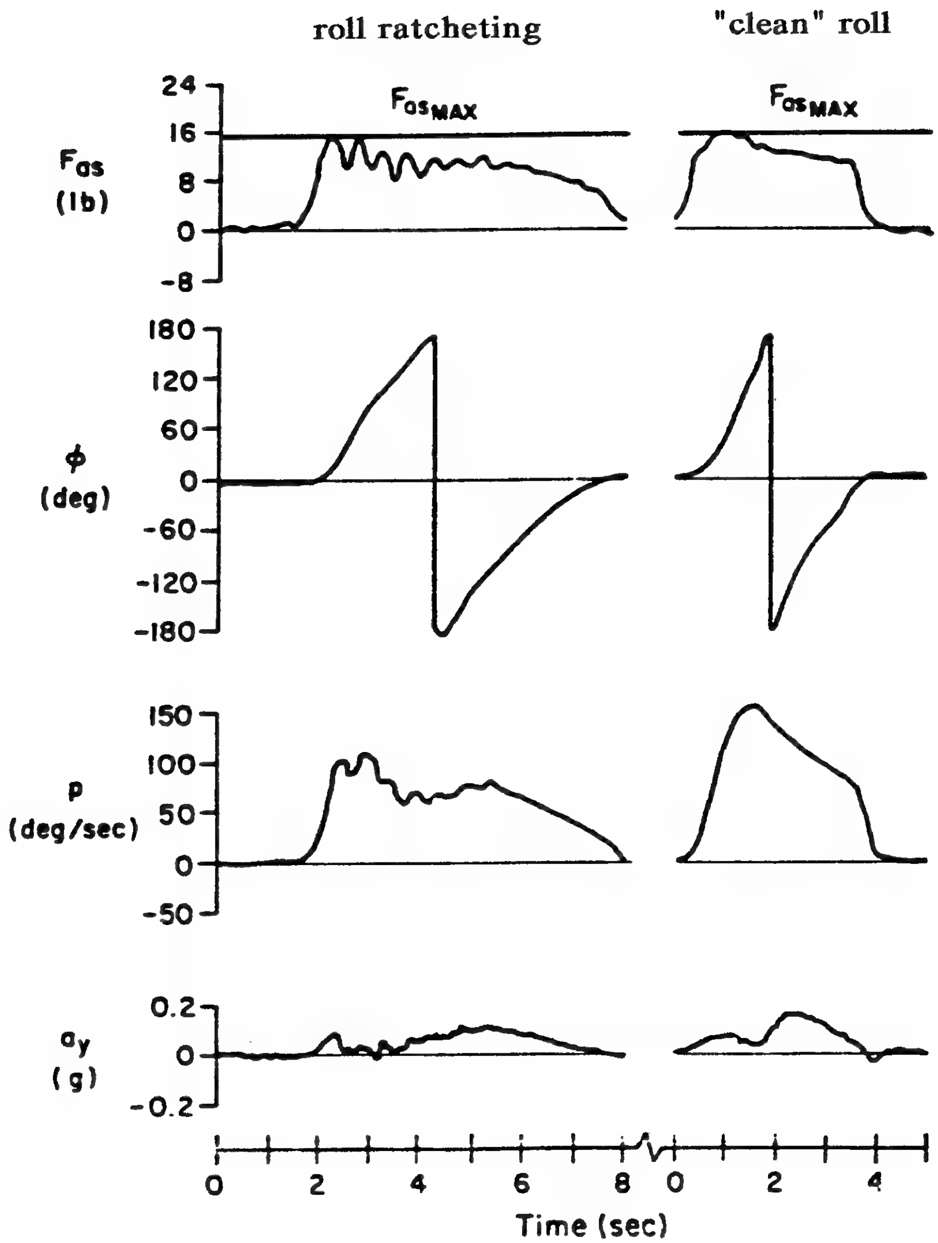


Fig. 23 Roll ratchet encounter in YF-16 in rolling maneuver compared with similar maneuver with no ratchet (Hoh, et al, 1982).

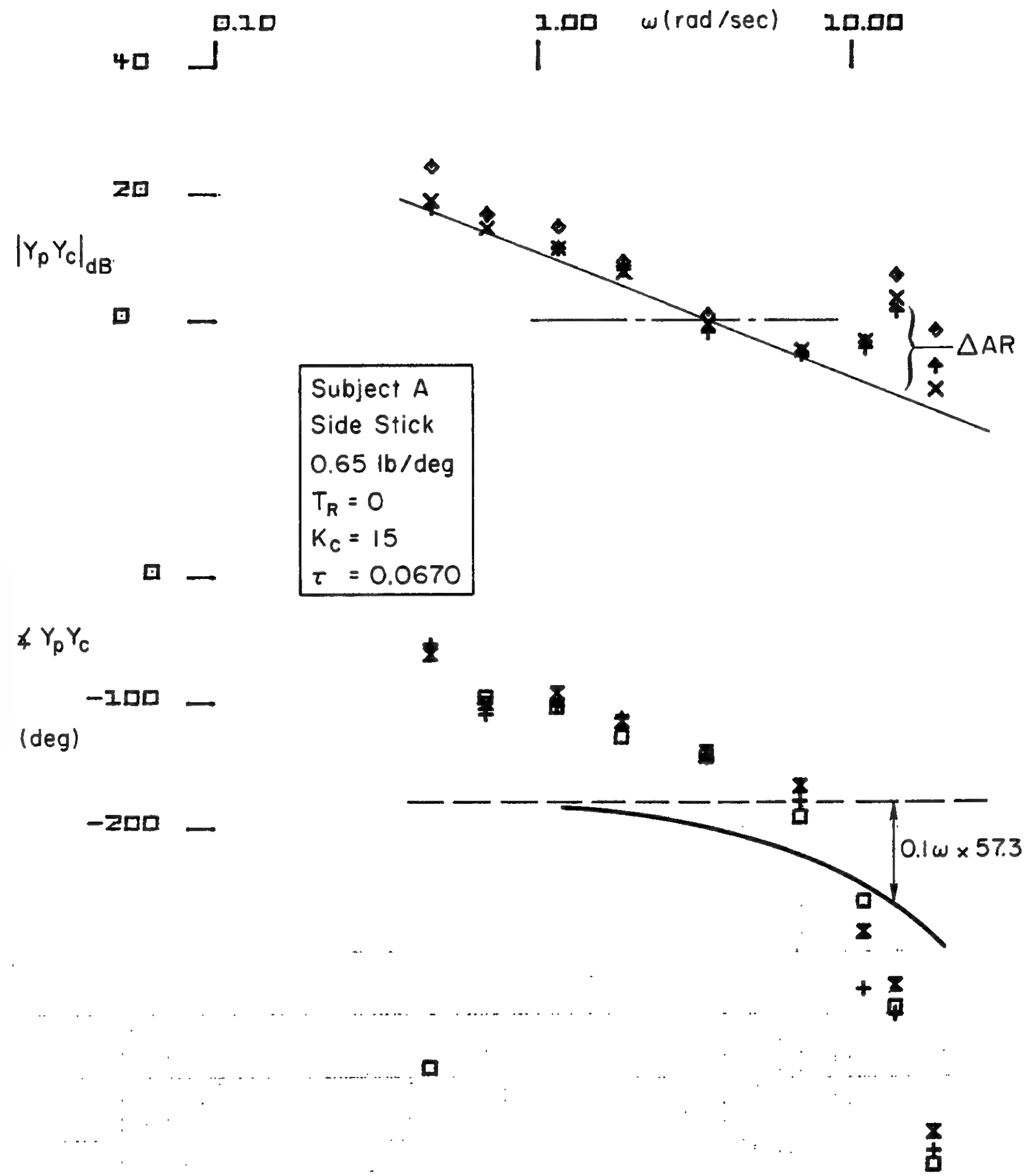


Fig. 24 Bode plot of measured pilot–vehicle transfer functions for position command force–feel system (Johnston and Aponso, 1988).

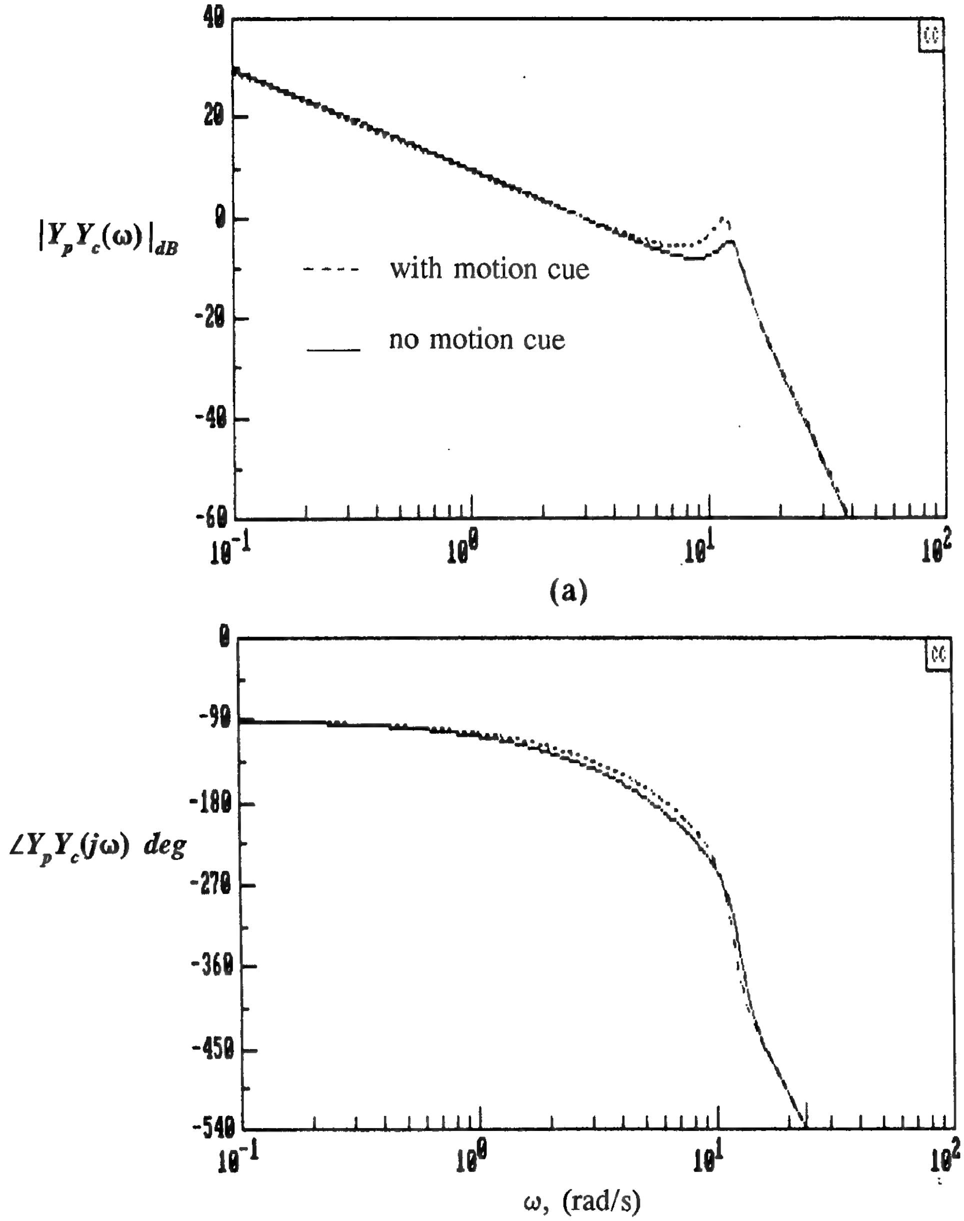


Fig. 25 Bode plots of pilot-vehicle transfer functions obtained from model of Fig. 12, position command (sensing) system, (Hess, 1992b).

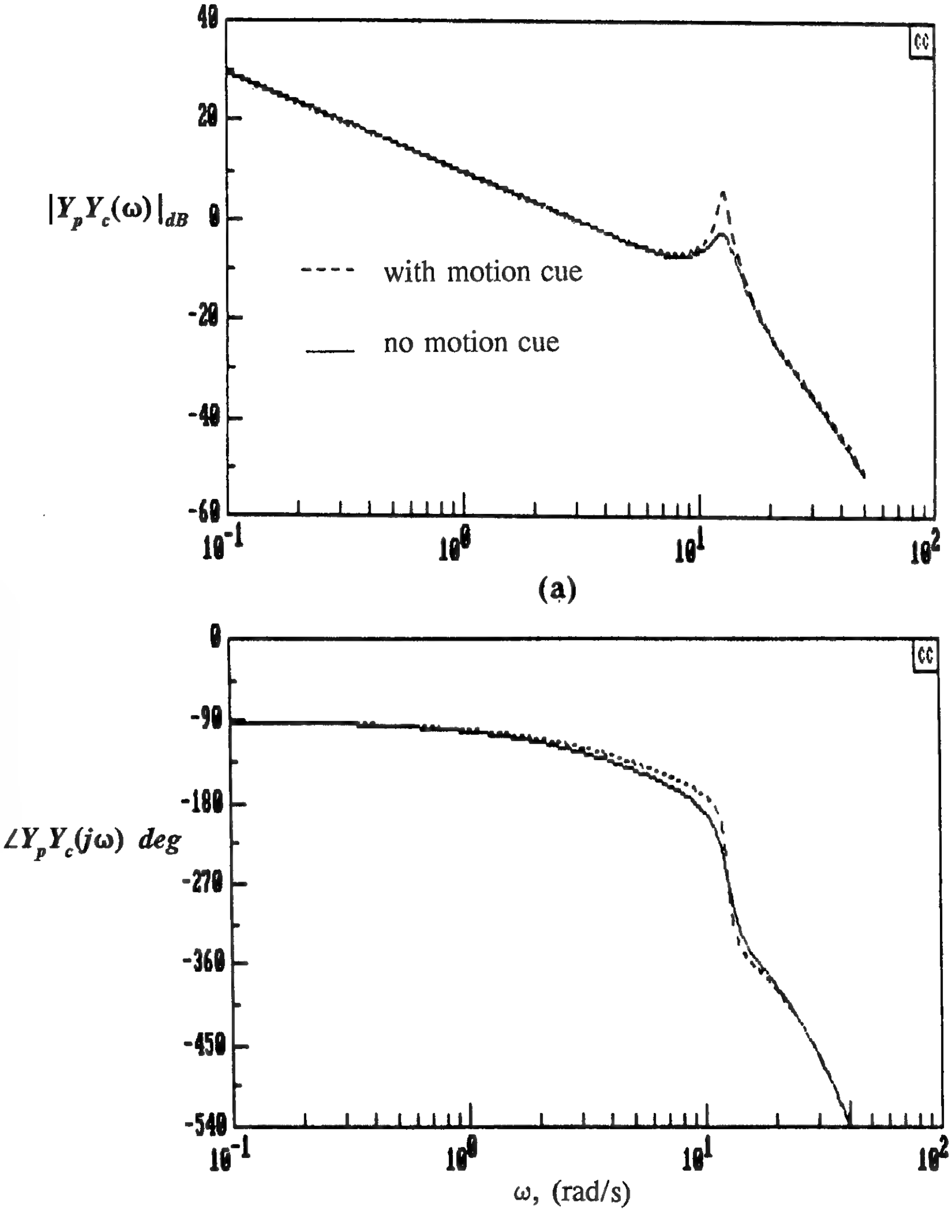


Fig. 26 Bode plots of pilot-vehicle transfer functions obtained from model of Fig. 12, force command (sensing) system, (Hess, 1992b).

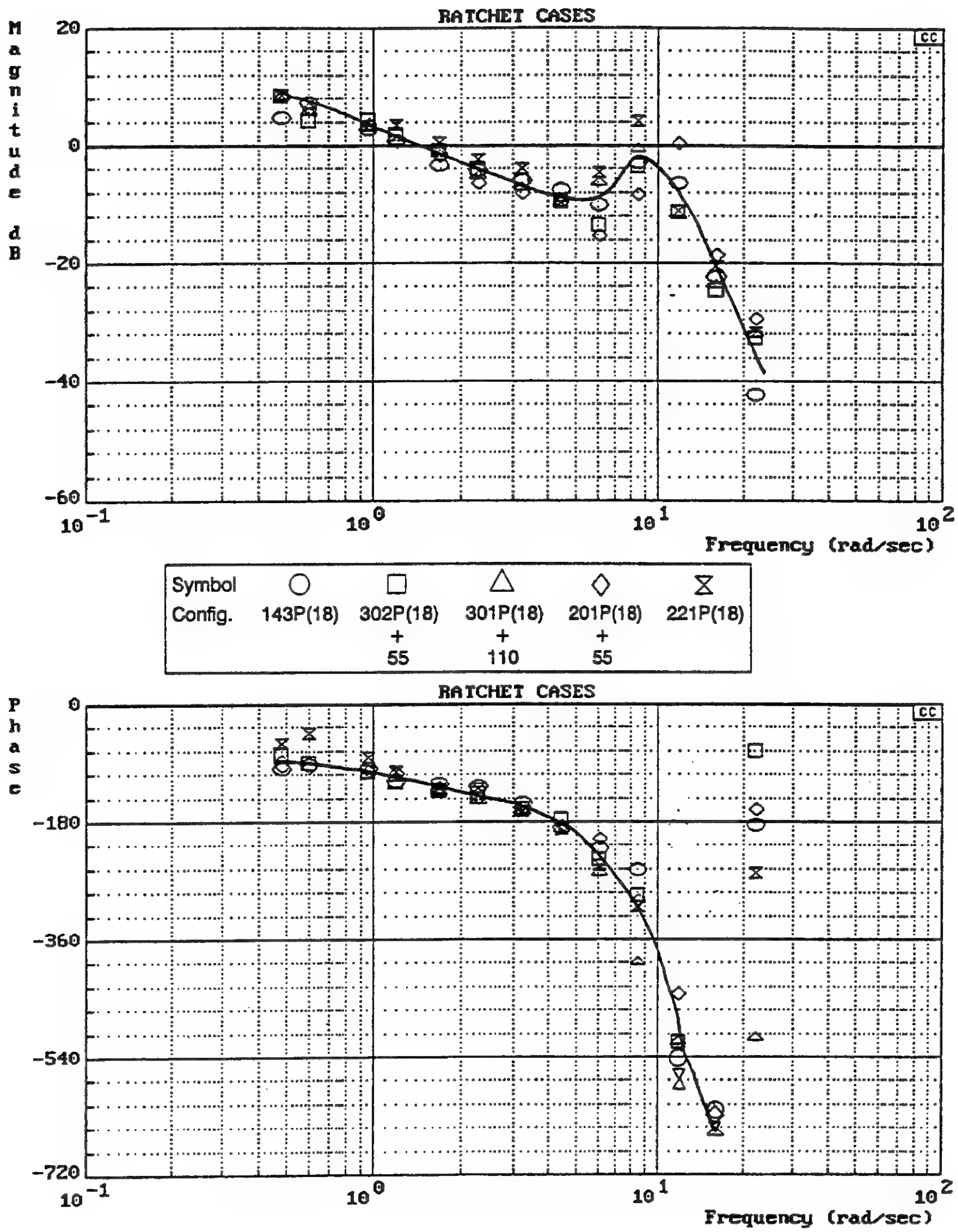


Fig. 27 Bode plot of pilot–vehicle transfer function obtained from flight data in which roll ratchet occurred (Mitchell, 1992).

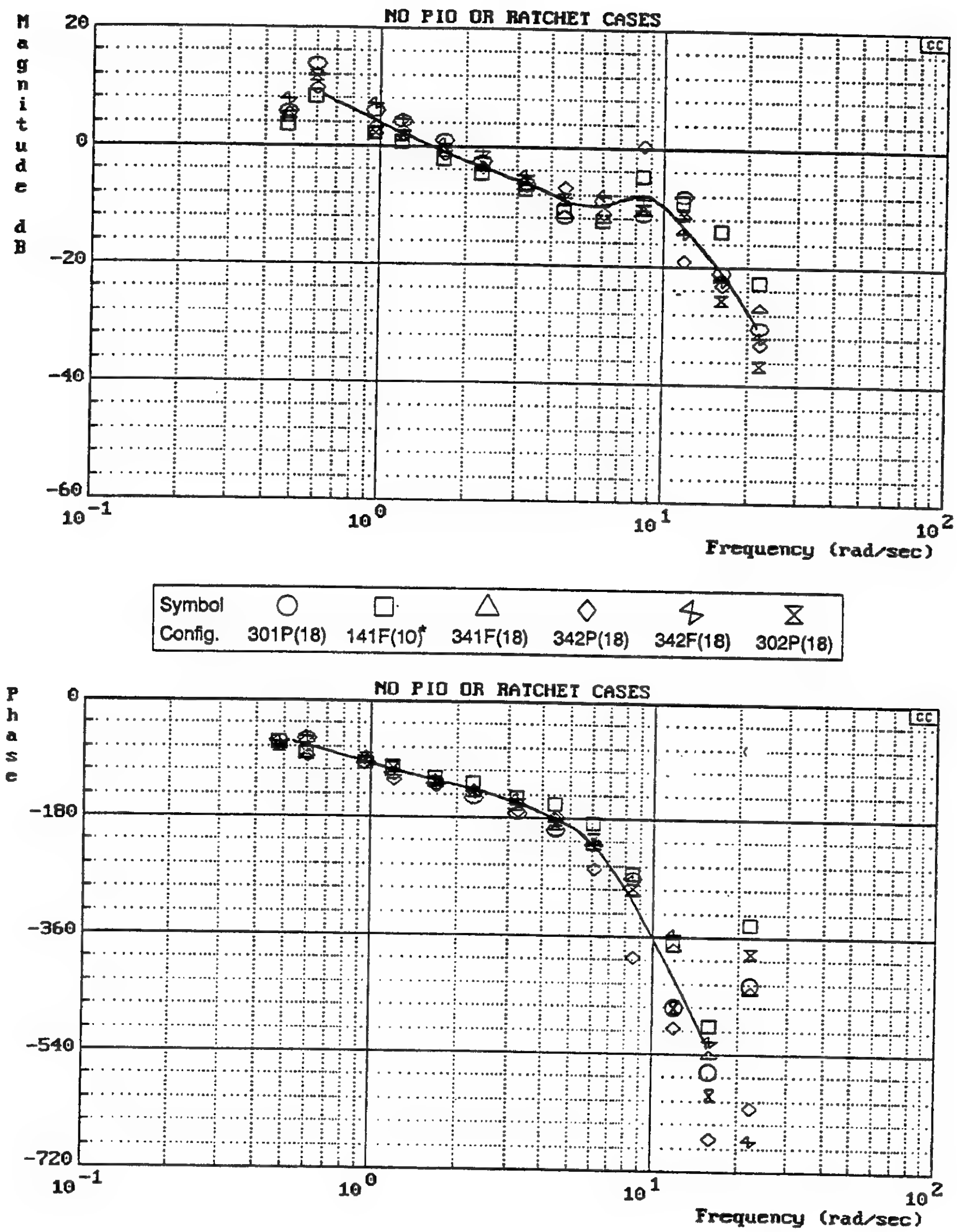


Fig. 28 Bode plot of pilot-vehicle transfer function obtained from flight data in which roll ratchet did not occur (Mitchell, 1992).

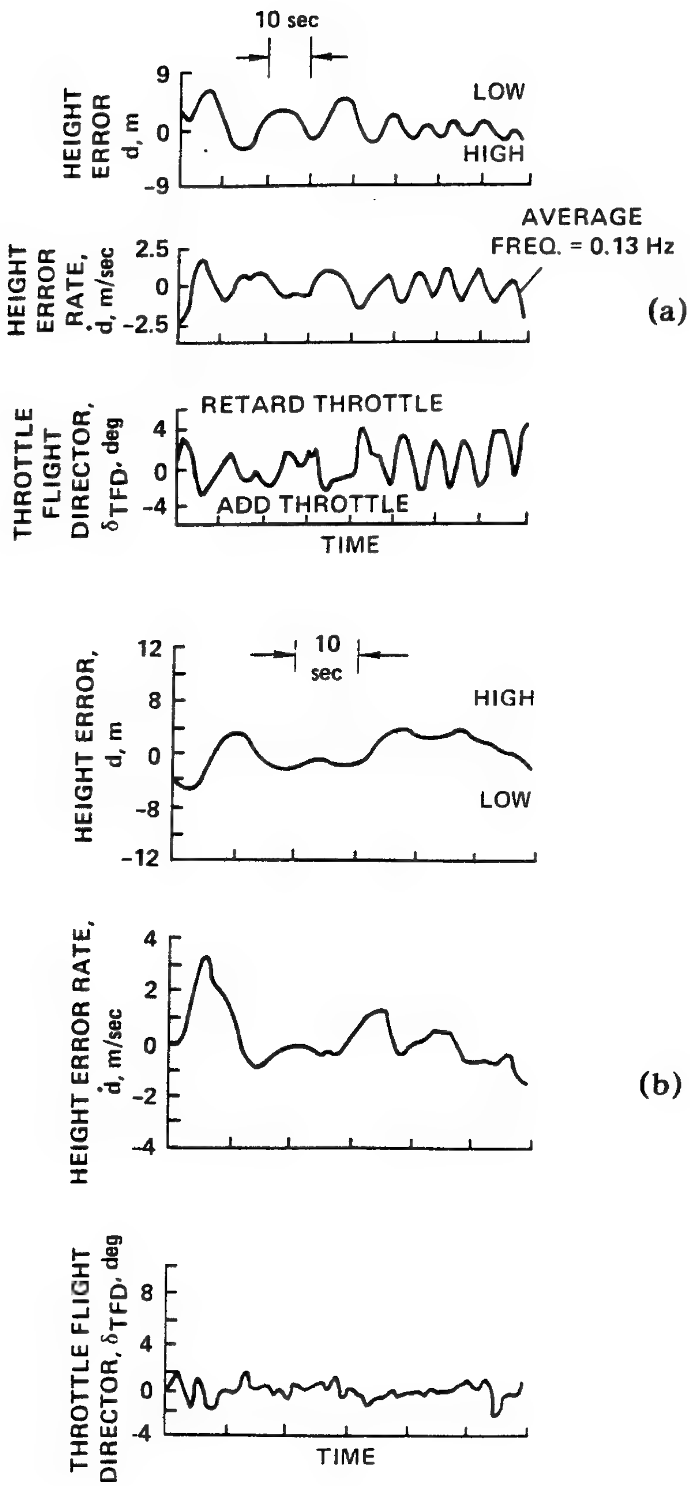
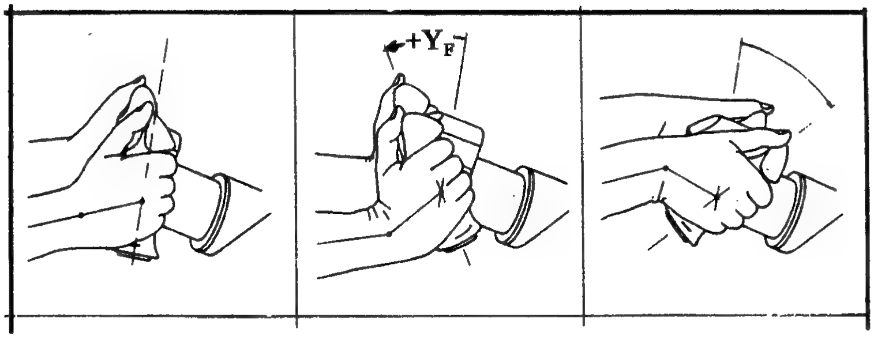


Fig. 29 Glide slope tracking and throttle movement (a) original flight director; (b) modified flight director (Hindson, et al, 1981).



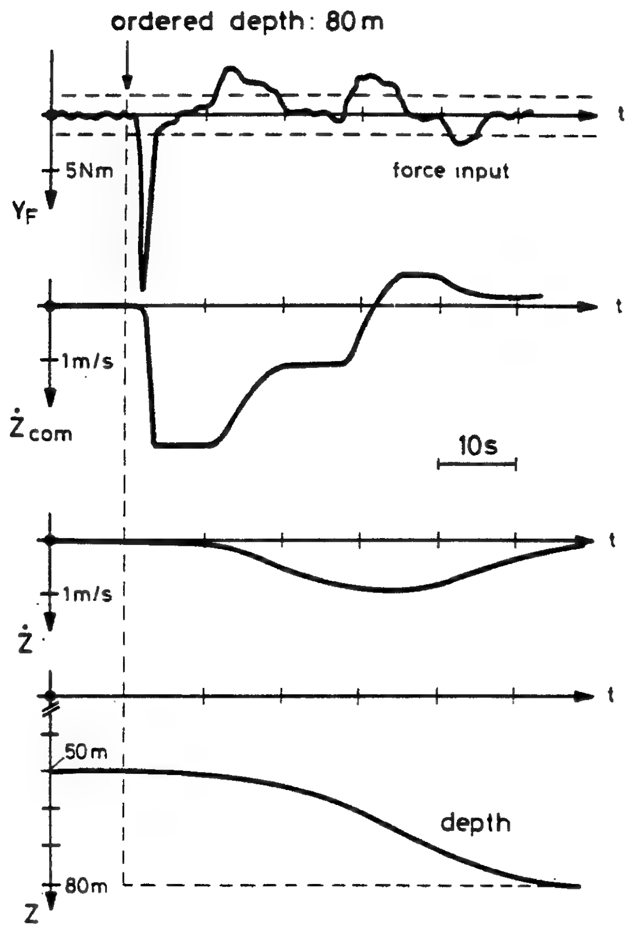


Fig. 30 Time histories of simulated submarine depth transition (Boller and Kruger, 1979).

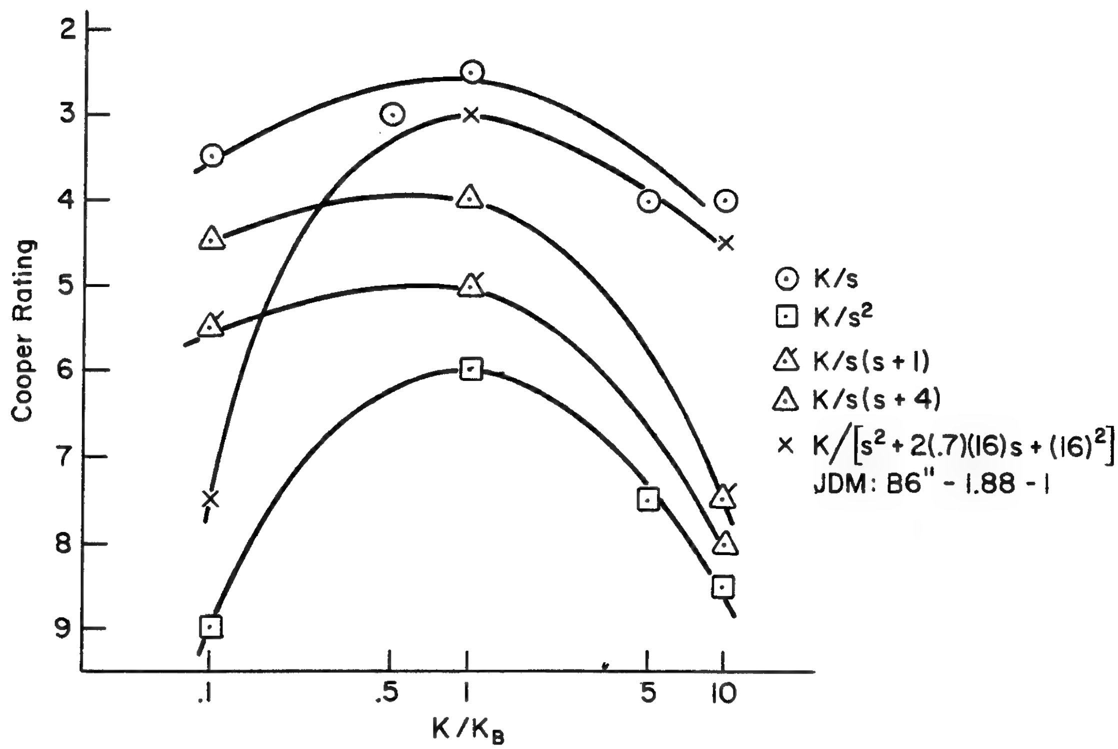


Fig. 31 The variation of pilot rating with controlled element gain (McDonnell, 1968).

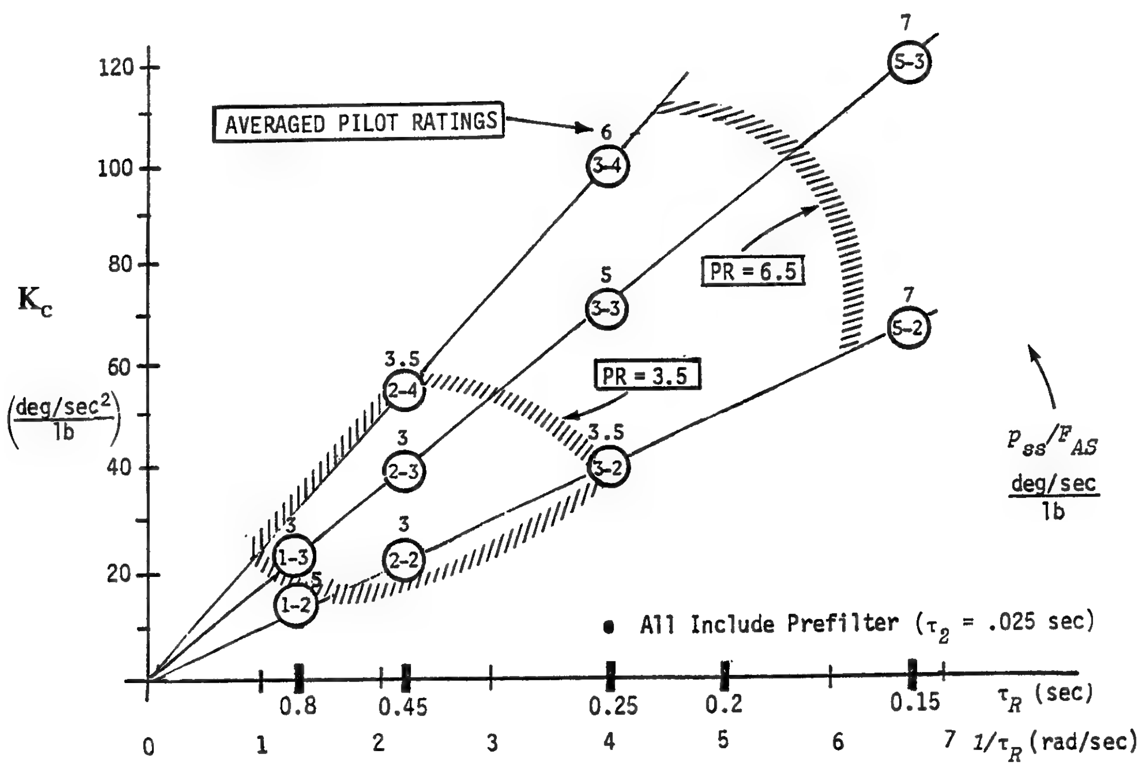


Fig. 32 The variation of pilot rating with command gain and roll mode time constant (Smith, et al, 1981).

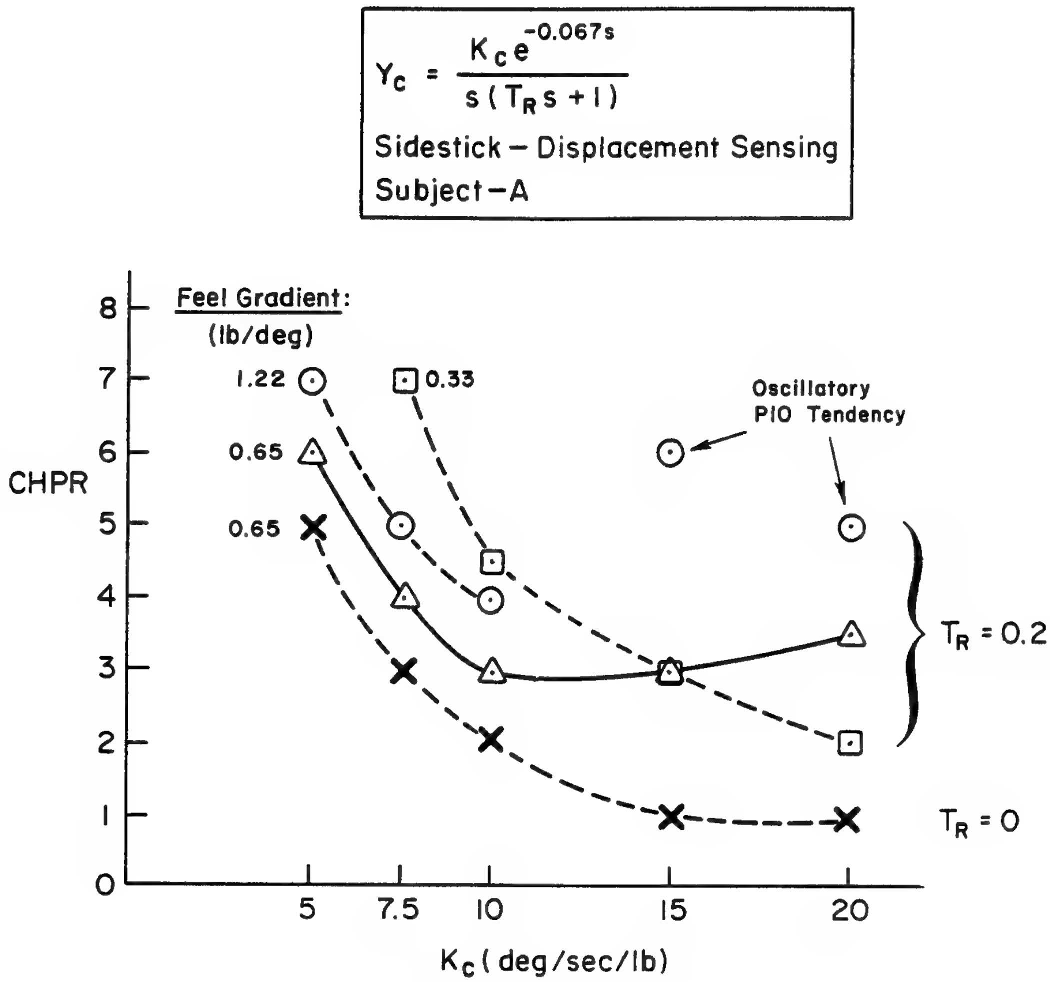


Fig. 33 The variation of pilot rating with command gain and force-feel system gradient (Johnston and Aponso, 1988).

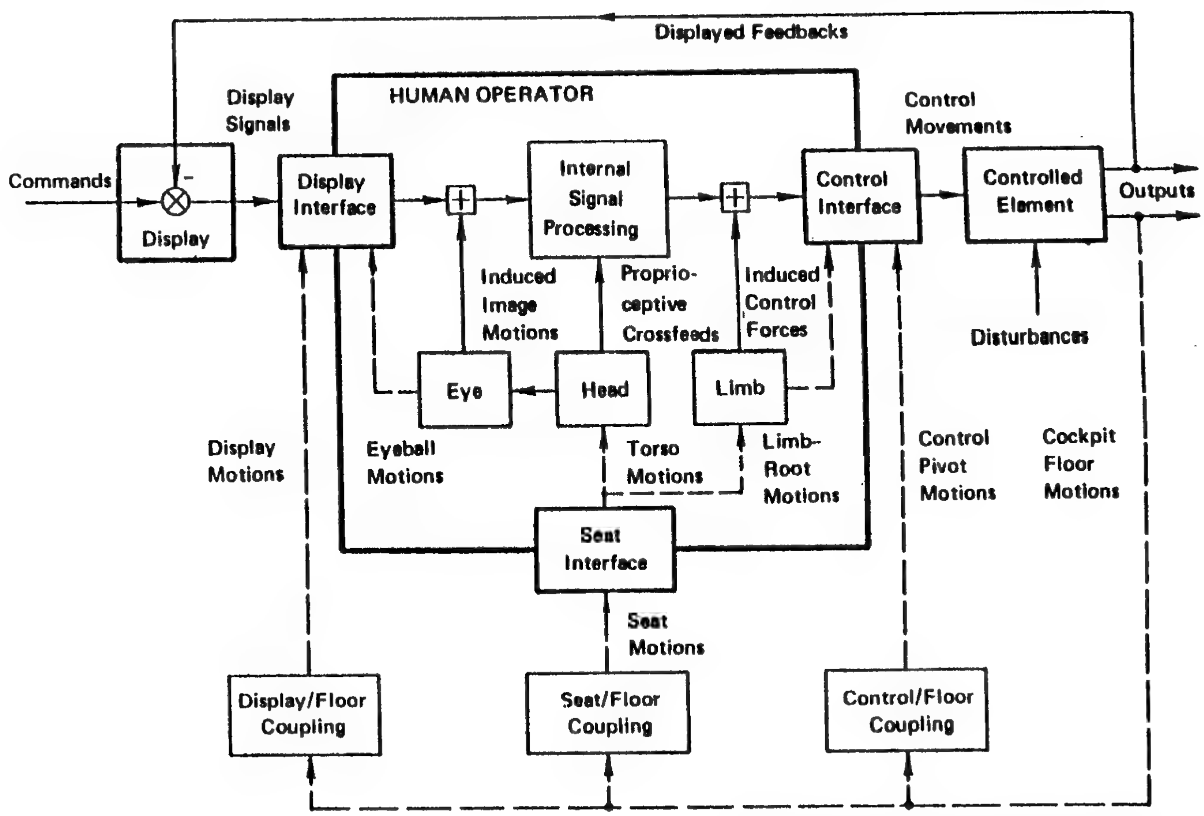


Fig. 34 Biodynamic interfaces for man-machine control (Jex, 1971)

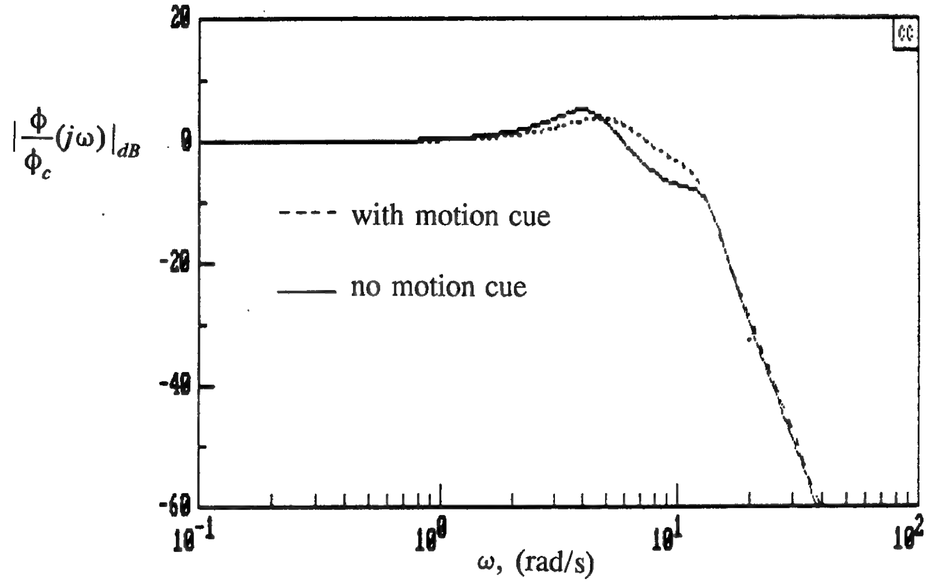


Fig. 35 Bode plots of closed-loop transfer functions, position sensing force-feel system (Hess, 1990b).

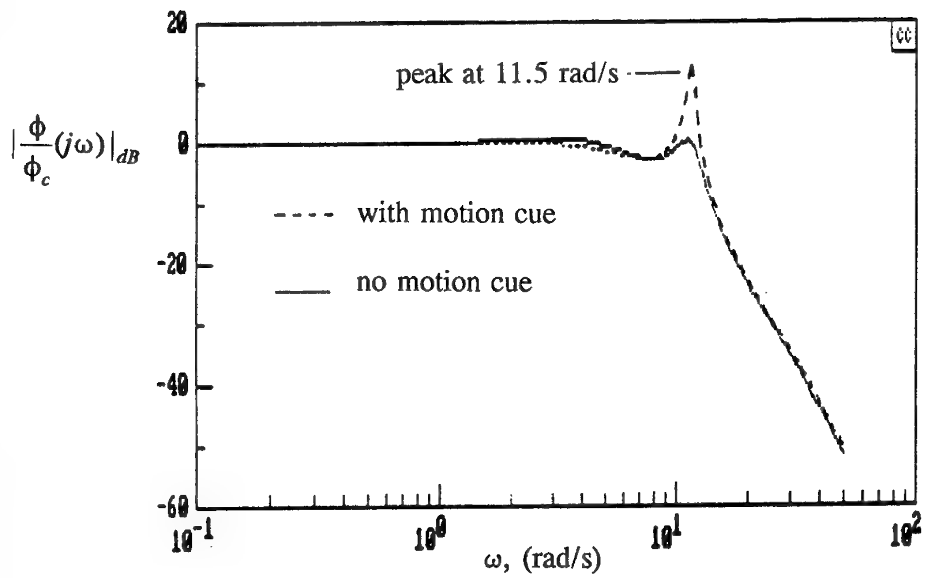


Fig. 36 Bode plots of closed-loop transfer functions, force sensing force-feel system (Hess, 1990b).

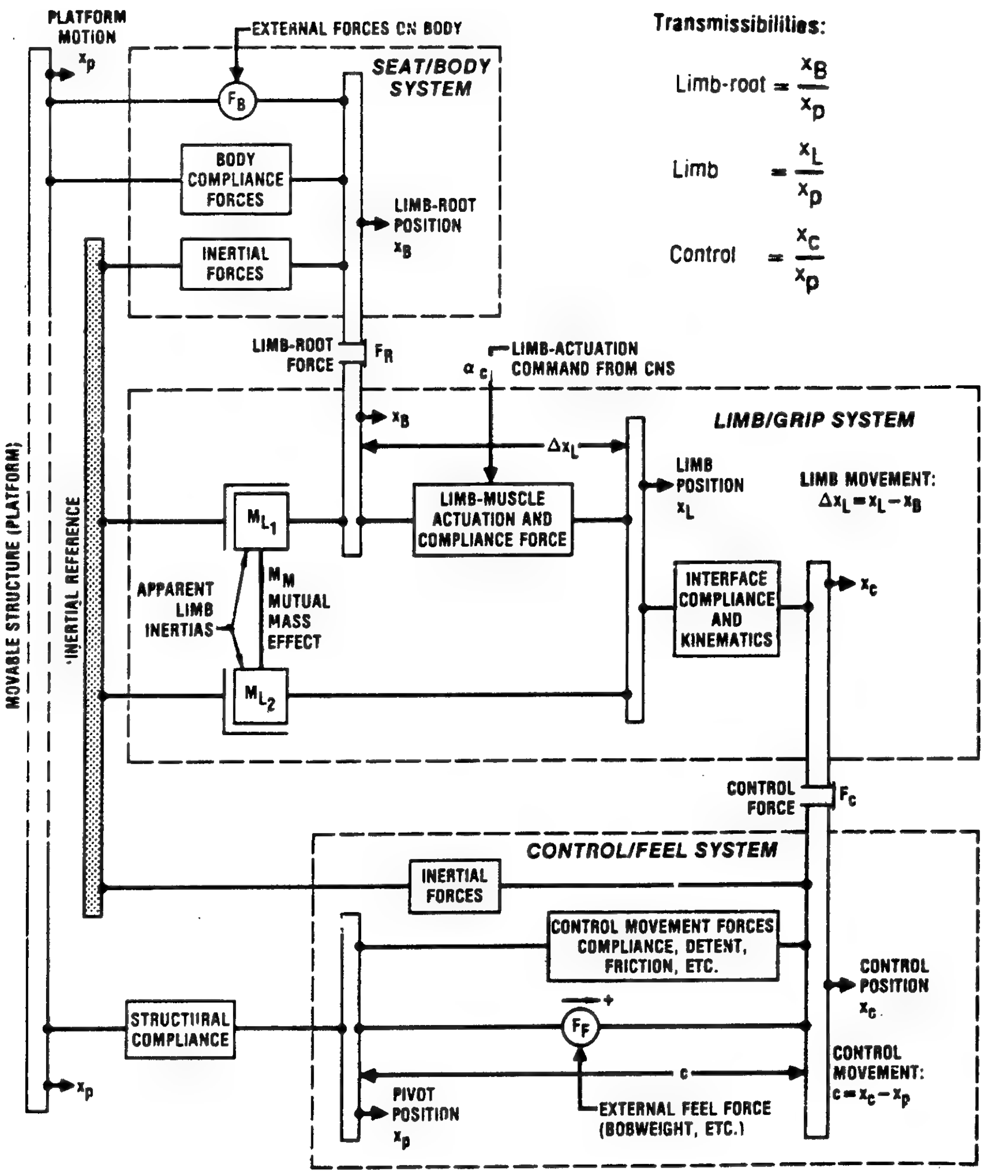


Fig. 37 A model for biodynamic interference in manual control (Allen, et al, 1973).

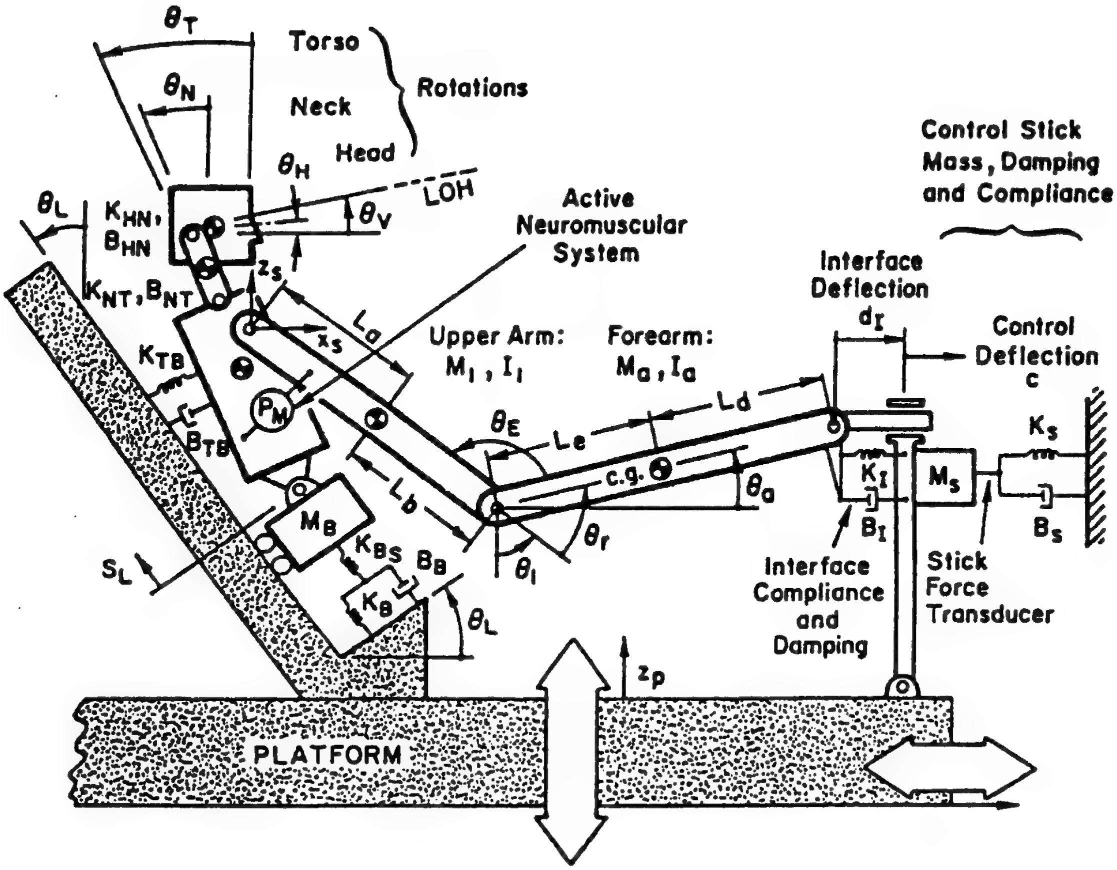


Fig. 38 A biomechanical pilot model for pitch axis control (Reidel, et al, 1980).

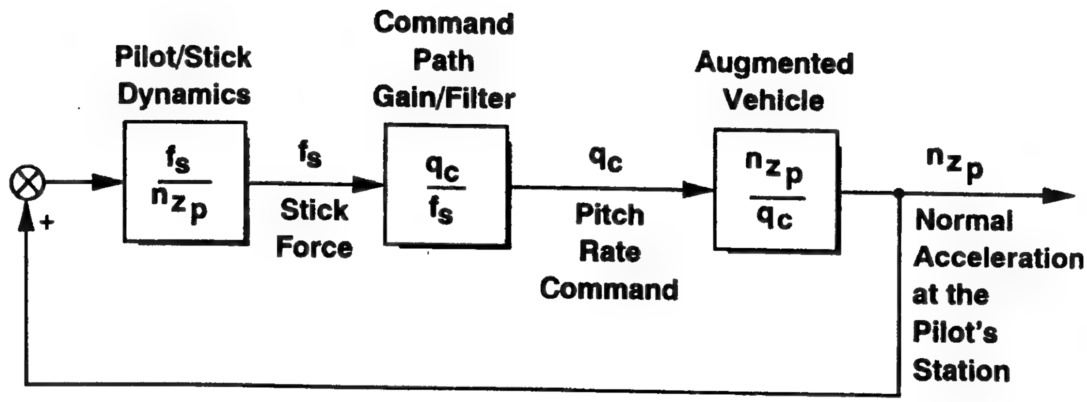


Fig. 39 Biodynamic analysis of a manual control problem (Chan, et al, 1992).

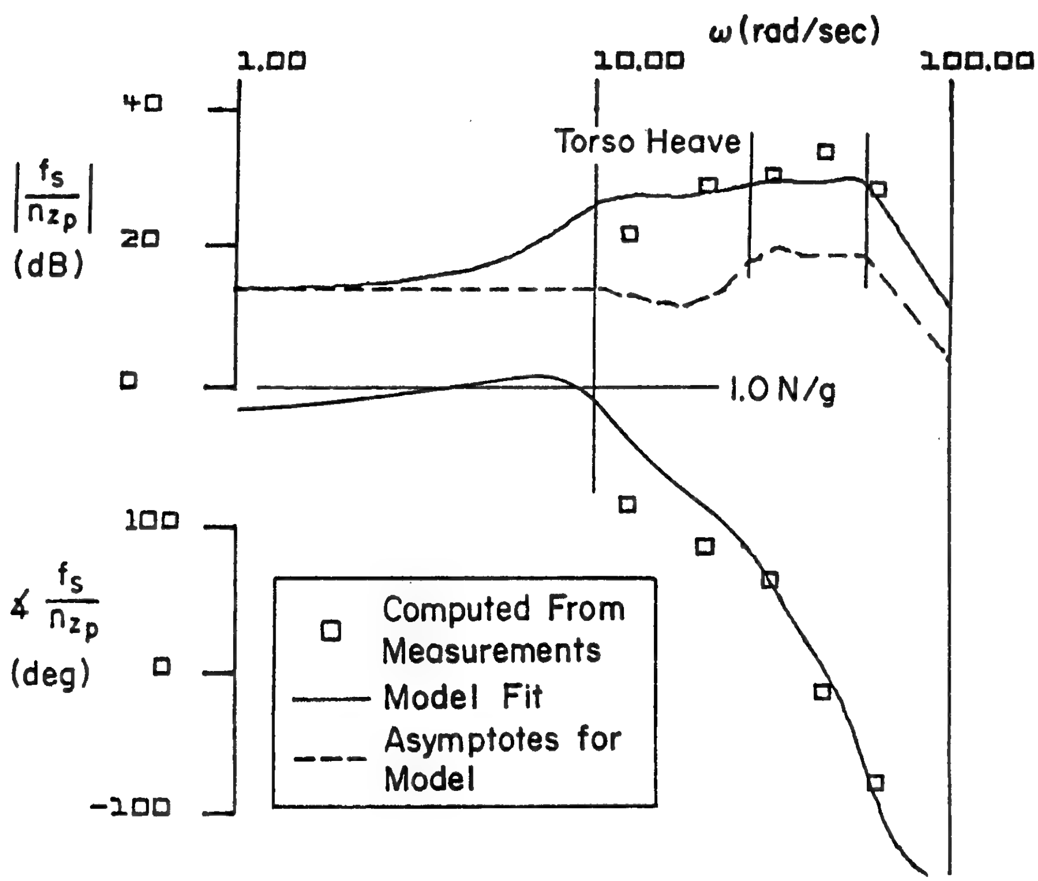
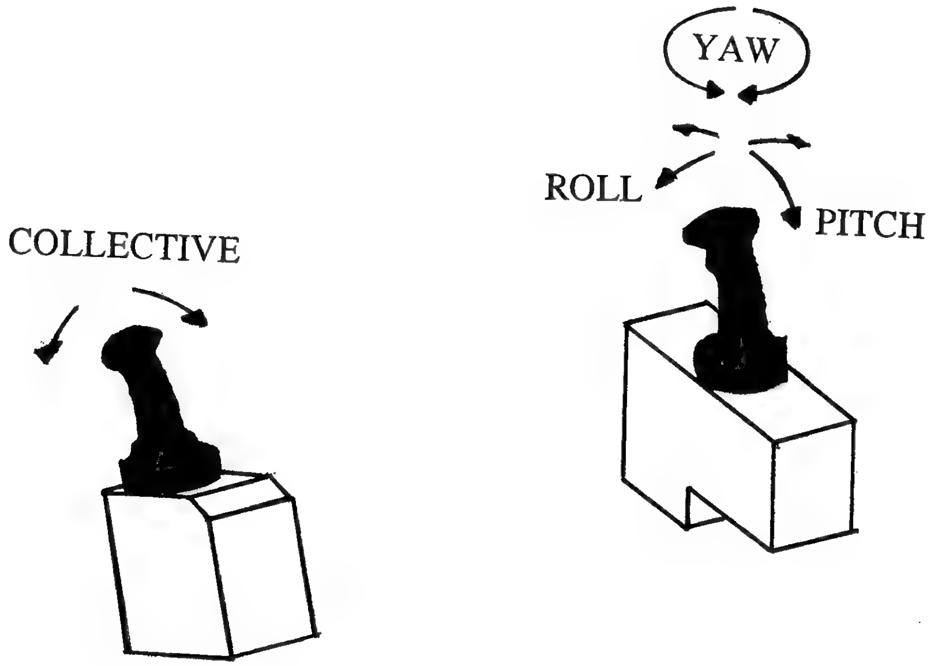


Fig. 40 Frequency response of human transmissibility (Allen, et al, 1973).



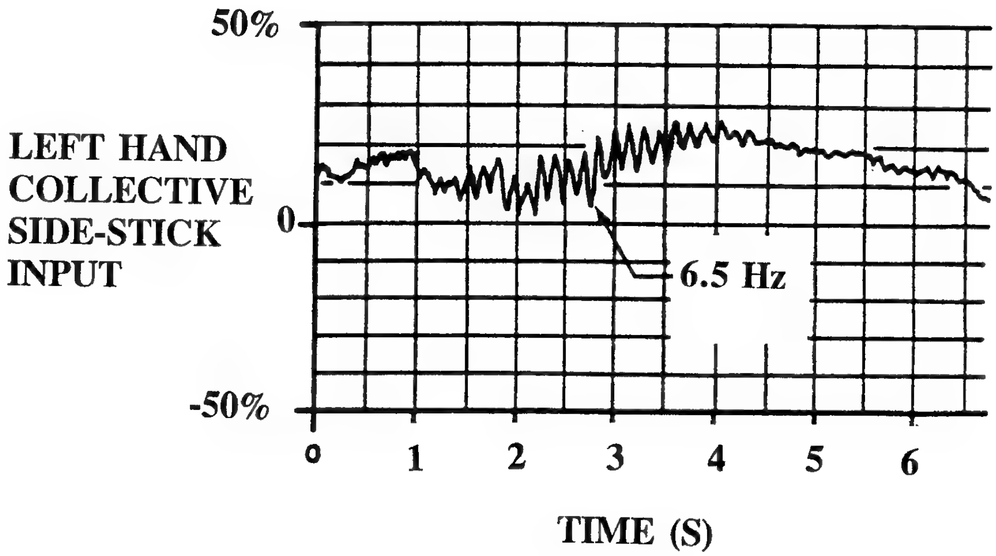


Fig. 41 ADOCS collective controller and time history of biomechanical vibration feedthrough.

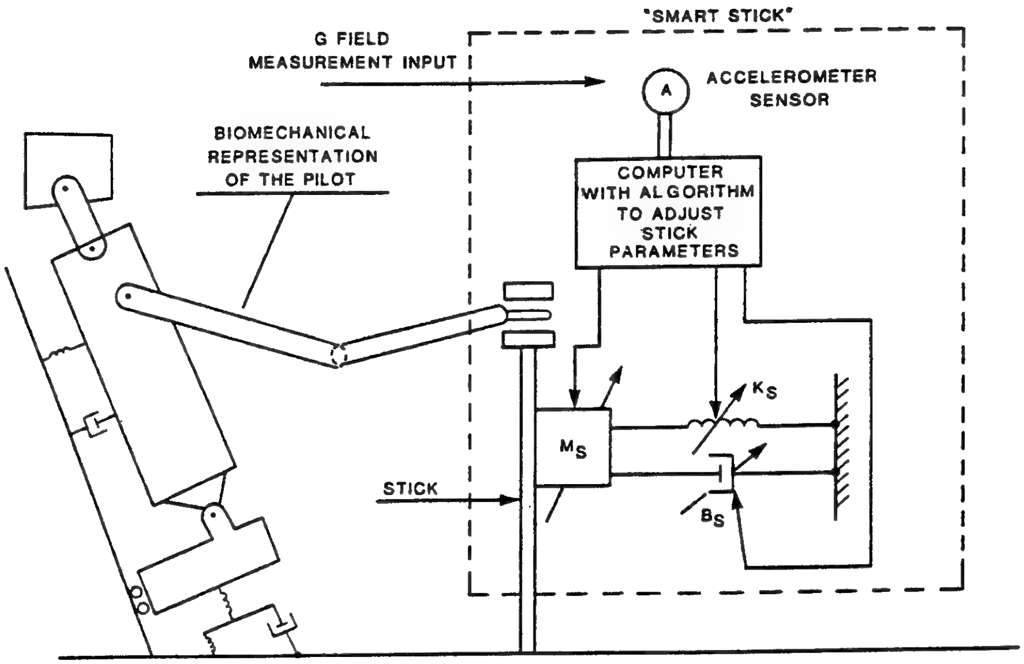


Fig. 42 The "smart stick" (Repperger and Frazier, 1983).

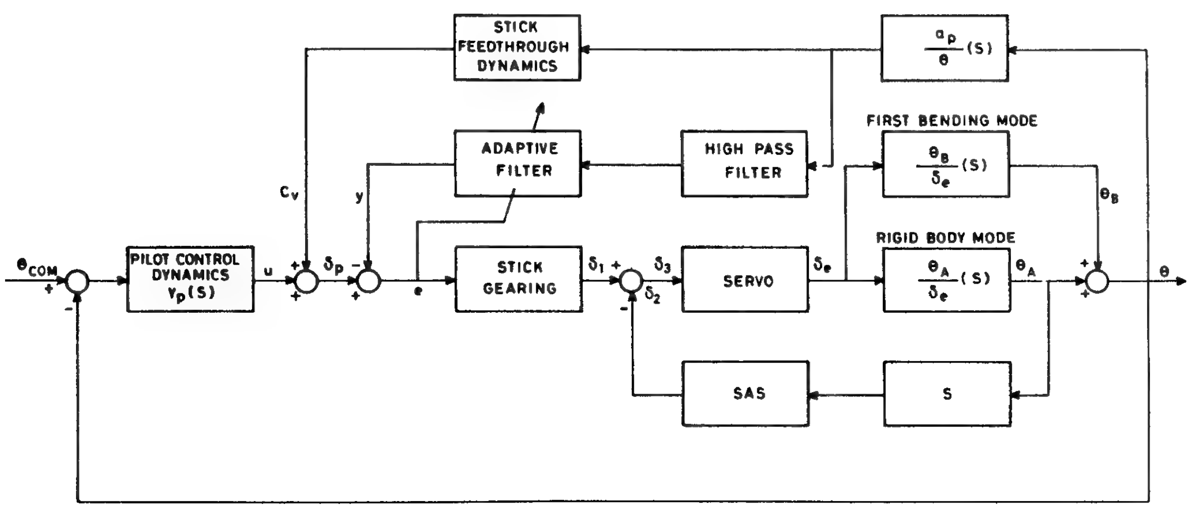


Fig. 43 LMS adaptive filtering scheme for YF-12 computer simulation (Velger, et al, 1984).

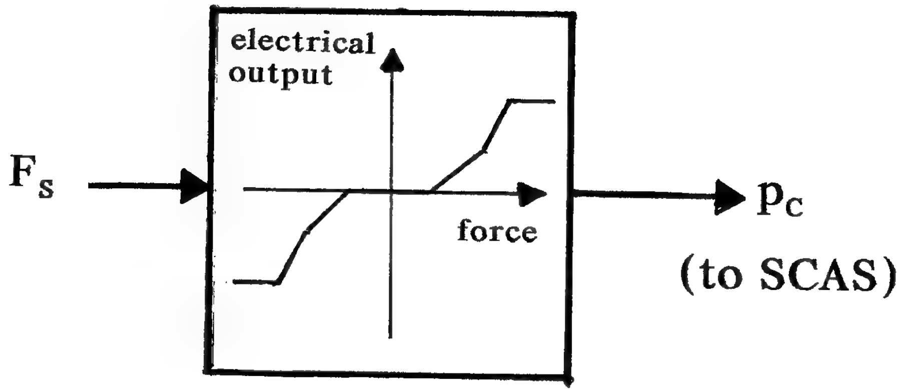


Fig. 44 A nonlinear command gradient for a stability and command augmentation system.

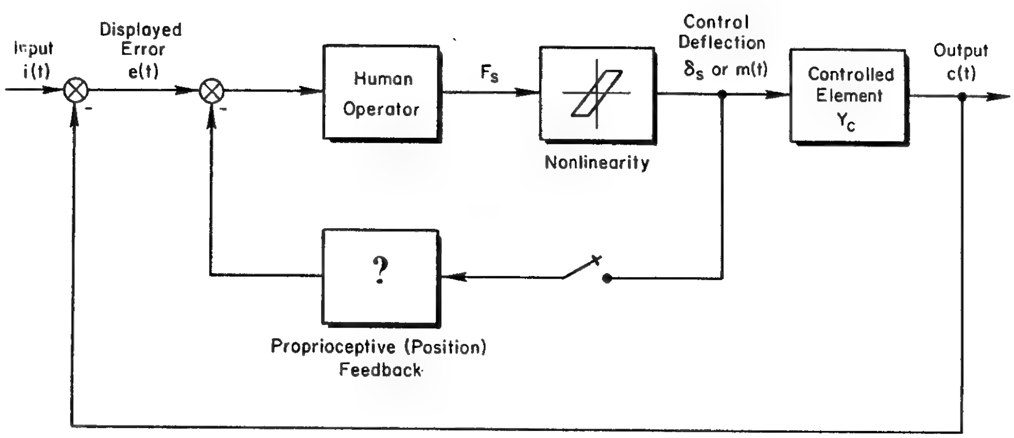


Fig. 45 Compensatory tracking with force-displacement nonlinearities (Graham, 1967).

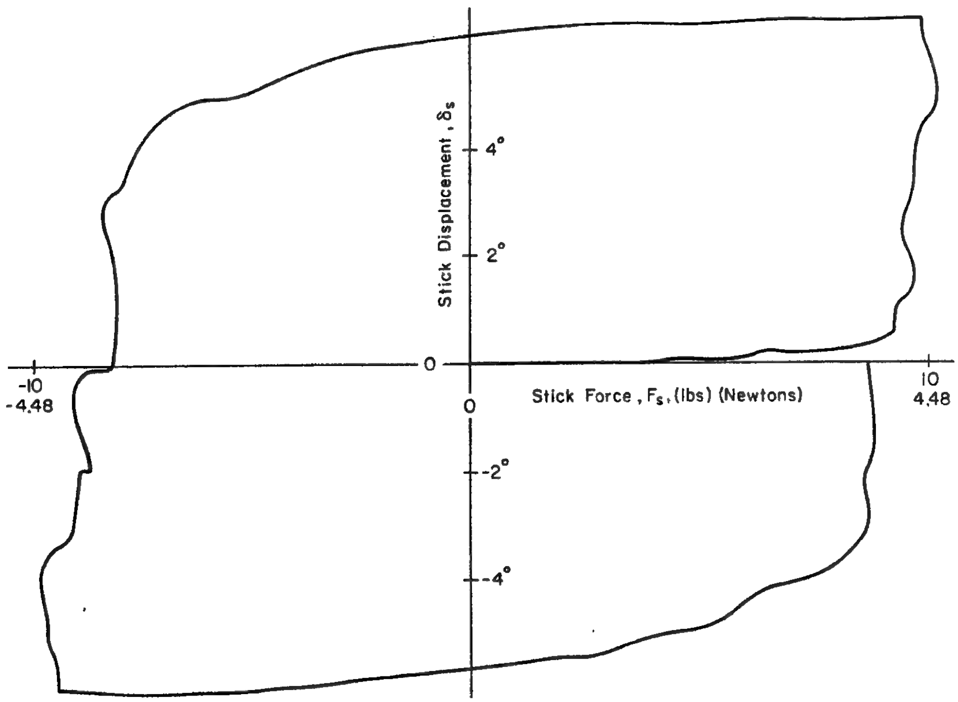


Fig. 46 Stick displacement versus stick force for sinusoidal stick motion with stick friction = 10 lbf (stick springs disconnected) (Graham, 1967).

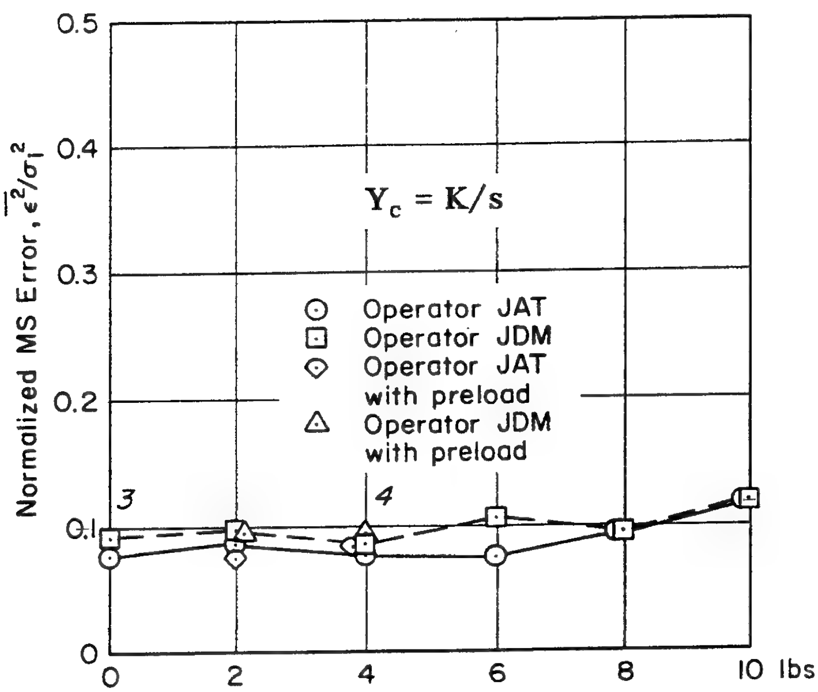


Fig. 47 Normalized tracking error scores for different levels of stick friction (Graham, 1967).

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A flight investigation of short-period longitudinal oscillations of an airplane with free elevator

NACA report No. 709, 1941 Jones, Cohen
An analysis of the stability of an airplane with free controls

NACA Report No. 791, 1944 Greenberg, Sternfield
A theoretical investigation of longitudinal stability of airplanes with free controls including the effect of friction in control system

NACA Report 798, 1944, Jones, Greenberg
Effect of hinge moment parameters on elevator stick forces in rapid maneuvers

Jnl. Royal Aeronautical Society, 49, 431 1945 Morgan, Thomas
Control system design

- Includes early table of allowable stick forces and displacements.

NACA Memo Report L6E20, 1946, Johnson
Flight investigation to improve the dynamic longitudinal stability and control-feel characteristics of the P-63A-1 airplane with closely balanced experimental elevators

NACA TN 1060, 1946 Phillips
An investigation of additional requirements for satisfactory elevator control characteristics

- Three aircraft with bobweights and closely balanced controls were unsatisfactory in rapid maneuvers though satisfactory in steady turns.

RAE Report Aero 1994 Thomas, Lofts

Analysis of wind tunnel data on horn balance.

- Shielded and unshielded horn results from a wide variety of aircraft.

RAE Report Aero 2163, R&M 2502, 1952 Thomas, Crabbe
Note on the Frise aileron

NACA RM L53 L28 (NASA/TIL/6780) Mayer, Hamer, Huss
A study of the use of controls and the resulting airplane response during service training operations for four jet fighter airplanes

- Actual rates and amounts of control motion used by service pilots during squadron training missions. (3 had no power controls, 1 had elevator power boost.) Very little rudder was used at high speeds.

Harvard School of Public Health (1953) McFarland, Damon, Stoudt, Moseley, Dunlop, Hall
Human body size and capability in the design and operation of vehicular equipment

- Comprehensive survey, recommendations, and descriptions of problems arising from incorrect design.

RAE Report Aero 2517, R&M 3094, 1954 Neumark, Collingbourne, Thomas
A case of longitudinal stick-free dynamic instability of an aircraft fitted with power-operated control, g-restrictor and spring feel

NACA RM A54 I28 Abromovitz, Van Dyke Jnr.
Effect of stick force gradient and stick gearing on the tracking accuracy of a fighter aeroplane

- Says neither variable had much effect over a range of 0·2 to 5·9 lb/g, and 0·07 to 0·7 inches/g. Possibly the task was too easy.

NACA TN 3428, 1955, Faber
Ground simulator study of the effects of stick force and displacement on tracking performance

WADC TR 55-299, 1955, Harper
Flight evaluations of various longitudinal handling qualities in a variable stability jet fighter

- Preferred stick force was 8 lb/g, displacement 0·2 in/g, i.e. stick stiffness 40 lb/in

Douglas Report ES26175, 1956, Abzug, Thorndike
Effects of flight control system mechanical characteristics on airplane controllability

WADC TR-56-107, 1956, Senders, Bradley
Effect of backlash on manual control of pitch of a simulated aircraft

WADC TR 56-258, 1956, Harper
Flight evaluations in variable-stability airplanes of elevator control motion gradients for high speed bombers

NACA RM L56 L28a Sjoberg, Russel, Alford
Flight investigation of a sidestick with electronic control system

- Grumman Panther with rate or displacement command. generally liked but only limited range of manoeuvres with no landings. Zero speed trim with no stall warning.

WADC TR 57-719 Parts 1 and 2 Chalk
Additional flight evaluations of various longitudinal handling qualities in a variable stability jet fighter

- Suggests that there is an ideal "stick rate" which influences stick force/g for different displacement/g

WADC TR 57-155 Newell
Effects of breakout force on longitudinal handling qualities

- Variable stability B-26, with stick forces of 35 to 60 lb/g, breakout forces of 0, 3·5 and 7 lbs. In no case did friction improve handling and could even lead to instability.

WADC TR-57-326, 1957, Rockway
Effects of variations in control deadspace and gain on tracking performance

NACA TN 4064, Phillips, Brown, Mathews
Unsatisfactory control characteristics involving instability of pilot-airframe

- Mainly concerns friction in controls

NACA TN 4171, 1957, Bressenden
Some ground measurements of forces applied by pilots to a side located aircraft controller

IAS Preprint No. 854, 1958 Potocki
Broad outline of aircraft feel: pilots' appreciation

- Discusses feel systems and resulting stick forces. Stick force signalling proposed.

NACA TN 4202, 1958, Faber
Qualitative simulator study of longitudinal stick forces and displacements desirable during tracking

NACA TR 1348, 1958, Brown
Ground simulator studies of the effects of valve friction, stick friction, flexibility and backlash on power control system quality

- Stick friction should be more than valve friction, but not more than 3 lbs. Flexibility and backlash are detrimental between stick and power control unit, but can be tolerated if they affect only the feel system.

NACA TN 4297, 1958 Kuehnel, Sommer
Flight investigation of the acceptability of a small side-located controller used with an irreversible hydraulic control system

WADC TR 58-553 Rockway, Franks
Effects of variations in control backlash and gain on tracking performance

- There is a monotonic increase in system error with increasing backlash at all gain levels, with rates of increase higher with higher gains.

NACA TN 4257 Silveira, Maglieri, Brooks
Results of an experimental investigation of small viscous dampers

- Tests on several dampers giving different characteristics, e.g. $F \propto V, V^2, \sqrt{V}$. Internal heat generated affected answers greatly.

NACA RM L58 B14, 1958, Assadourian
Ground simulator studies of a small side located controller in a power control system

WADC TR 58-439
A summary of trim system problems, investigation, consideration and corrective actions.

- List of all trim problems found to date by the USAF on several aircraft.

SAE 171D Tsun-Yang Feng, Neil
Discussion of some design problems associated with artificial feel systems of airplanes with irreversible powered flight controls

- Describes Mach-trim and q-feel with bobweights and various compensations, and shows analysis of effect of feel system on stick free dynamics.

ARL/A 182 Frost
A direct method for estimating the effect of coulomb friction on free oscillations

- Method of separating out viscous and coulomb friction from oscillation traces.

IAS 59-134, Sjoberg
Flying qualities associated with several types of command flight control system

- No objections found to lack of speed trim generally, desirable in rapid speed changes.

Space Aeronautics, March 1960 Andreasson
Minimum manual controls.

- Description of small stick control system on an F-102.

NASA TN D-173 Russell, Sjoberg, Alford
Flight investigation of automatic stabilisation of an airplane having static longitudinal instability

- Pitch rate and normal acceleration demand systems. Side force stick seemed acceptable without simulated friction.

NASA TN D-348 Sadoff, McFadden, Heinle
A study of longitudinal control problems at low and negative damping and stability with emphasis on effects of motion cues

- A pencil controller in shirt-sleeve environment showed substantial improvement for high short period frequency low damping areas over center force command stick.

NASA TN D-367 Brown, Johnson, Mungall
Simulator motion effects on a pilot's ability to perform a precise longitudinal flying task

- Better performance in a moving cockpit than in a fixed one. Very high stick force gradient improved performance. Motion was most beneficial at zero force gradient.

NASA TN D-546 Andrews, Holleman
Experience with a three-axis side located controller during a static and centrifuge simulation of the piloted launch of a manned multistage vehicle

- Difficult to get co-ordination at high g with forces suitable for low g.

NASA TN D-632, 1961 Faber, Crane
A longitudinal control feel system for in-flight research on response feel

- Feel jack has differential pressure controlled by electrohydraulic valve, with inputs from a_n, q, $\dot{q}$, stick position and stick rate.

NASA TN D-912 Crane, Sommer
Effects of control feel configurations on airplane longitudinal control response

- Grumman Tiger fitted with feel system responsive to stick position and rate, a_n, q, and $\dot{q}$. Indicates that a_n feel tends to destabilise the short period, which can be balanced by $\dot{q}$ feel.

Bu Aer Report AE-61-4III
The Human Pilot

- Discusses the rate at which pilots can move a stick as function of spring gradient.

AGARD Report 366 Westbrook
Simulation in modern aerospace vehicle design

- Review of simulation facilities in USA, with 212 references including 47 to variable stability, control and feel aircraft.

NASA TN D-1488 Garren, Assadourian
VTOL height control requirements in hovering as determined from motion simulator study

- Desirable controller sensitivity found to be 0·25 g/in to 0·15 g/in for damping/mass ratios of 1·0 to 0 respectively.

NASA TN D-1552 Sadoff
A study of a pilot's ability to control during simulated stability augmentation system failures

- A pencil grip sidestick was better than a fixed center force stick.

ASD-TDR-61-362 Kidd, Harper
Fixed base and in-flight simulations of longitudinal and lateral-directional handling qualities for piloted re-entry vehicles.

- Compared sidestick sensitivities with earlier centre stick controller results.

AGARD Report 365 Rathert, Creer, Sadoff
The use of piloted flight simulators in general research

- Motion cues become important where motions hinder the pilot in making desired control inputs, e.g. with very powerful or sensitive controls. (Spurious accelerations in centrifuges cause difficulties and in general these should be used at a 3g datum.)

Flight 22nd Feb. 1962 Bedford, Merewether
"VTOL is simple - keep it so"

- Description of P.1127 and flight controls

ASD-TR-61-603, 1962 Graves et al
Study and development of an electric sidestick controller for aerospace vehicles

NATC TR-FT2123-62R-64, 1964
Flight evaluation of a side hand controller in an F-4A airplane

- Flat-hand controller liked, but had no advantages and some disadvantages.

NADC-ED-8471, 1964 Abrams, Farr
Controller design criteria and flying qualities requirements for a class of high performance stability augmented aircraft

Jnl. of Aircraft, Vol.1 No.1, 1964 Morris, McCormick, Sinacori
Moving base simulator study of an all-mechanical control system for VTOL aircraft

- Control system contained springs, dampers and bobweights to preshape the pilot's inputs. This produced similar 2 - 3½ Cooper ratings as for a rate stabilised aircraft.

FDL-TDR-64-60 Chalk
Flight evaluation of various short period dynamics at four drag configurations for the landing approach task

- Control gain at fixed spring rate selected by pilot was a function of the short period frequency and damping. The PSD of the pilot's stick movement was significantly affected by the short period and turbulence.

NASA CR-56 Besco, Depolo, Bauerschmidt
Manual attitude control systems: parametric and comparative studies of operating modes of control

- Implications for design of manual attitude control systems are presented for several types of control - pulse, repeated-pulse, on-off proportional acceleration, proportional rate, ratios of control power/disturbance, etc.

NASA TN D-2068 Lopez, Smith
Simulator studies of the manual control of vehicle's attitude using an on-off reaction control system

- Low control powers outside atmosphere. Very great saving of fuel results from use of finger-tip controller as opposed to hand/wrist operated stick, and pedal control was extremely wasteful.

LB31050 Douglas Aircraft Co. Inc.
Effects of static friction and force-displacement gradient on a discrete visual tracking task

- Established satisfactory force-gradient and static friction for small side-located sticks. Nose down should be slightly higher than nose up. (± 30° displacement, 6 lb nose up, 8 lb nose down. Friction about ±1 lb with no breakout force.)

TR 239-1 STI Inc. Jex
Summary of T-38A PIO analysis.

- Discusses influence of bobweight to spring feel ratios on dynamic stick force per g characteristics. A stick damper was of no use at levels which did not produce objectionable handling qualities.

NASA CR-63 Soliday, Schohan
A simulator investigation of pilot performance during extended periods of low altitude high speed flight.

- Control was affected by vertical g with center stick, more accurate control with a miniature sidestick (but the center stick had high friction).

Control Engineering March 1965
Artificial feel for servo-boosted manual controls

- Ling-Temco-Vought feel units for Boeing 727 with trim position interconnect and XC-142A V/STOL described.

AGARD Report 471 Lollar
A rationale for the determination of certain VTOL handling qualities criteria

- Optimum controller gain 10 in/rad. of attitude error for stiffnesses of 3 to 20 lb/in.

NASA TN D-2436 McLaughlin, Whitten
Pilot evaluation of dynamic stability characteristics of a supersonic transport in cruising flight using a fixed base simulator

- At short periods of 0·13 to 0·37 cps and damping of 0·06 to 0·36, preferred control sensitivity at spring gradient of 4 lb/in was 0·1 to 0·2 g/in, i.e. 40 lb/g to 20 lb/g.

Jnl. of Aircraft, Vol.2 No.3 1965 Cook
An automatic stall prevention control for supersonic fighter aircraft

- Describes the F-104 stick pusher and shaker, actuated by pitch rate and angle of attack.

NASA CR-512 Lewis
Kinematic transformations of several mechanisms

- Graphical results of displacement, velocity and acceleration for 7 mechanisms of various proportions.

AMRL-TR-65-158, 1965, Wasicko, Magdaleno
Effects of Non-linearities on Human Operator Tracking Performance: A Review of the Literature

AFFDL-TR-66-203, 1966, Knowles
Primary controller designs for jet transports

Princeton University Report No. 727 Seckel, Miller, Nixon
Lateral-directional flying qualities for power approach

- Control sensitivity discussed.

Aircraft Engineering, Sept. 1967 Lee
The aerodynamic design policy of the Handley Page Jetstream

- Discusses the control balance, with stick-free maneuver margin 1·08 x stick-fixed.

AFFDL-TR-67-53 Miller, Emfinger
Fly-by-wire techniques

- Discusses the design of compliant side stick manipulators.

AFFDL-TR-68-72, 1968, Winner
Development of three improved primary flight controller designs

AFFDL-TR-68-90, 1968, DiFranco
In-flight investigation of the effects of higher order control system dynamics on longitudinal flying qualities

- Includes variations of stick feel system dynamics.

FTC-TR-67-19, 1968, Keith, Richard, Marrett
Evaluation of longitudinal control feel system modifications proposed for USAF F/RF-4 aircraft

AFFDL-TR-69-3, 1969, Newell, Wasserman
In-flight investigation of the effect on PIO of control system non-linearities, pitch acceleration and normal acceleration bobweights

AFFDL-TR-69-40, 1969, Jenney
JB-47E fly by wire test program (Phase 1)

Aircraft Engineering Feb. 1970
"Harrier"

- Description of control system with q-feel, and vernier-coarse nose wheel steering.

RAE TR 70082 Woodfield, Budden
Flight trials of a switch operated thrust vector angle control system in a H.S. P1127 aircraft

- System gave much better controllability with only one hand needed for simultaneous thrust and vector control.

AIAA 70-1002, August 1970, Neal
Influence of bobweights on pilot-induced oscillations

- Discusses the double bobweight system.

AFFDL-TR-70-95, 1970, Rhoads
In-flight evaluation of four cockpit controller configurations in a variable stability airplane

Society of Experimental Test Pilots 1970 Report to the Aerospace Profession, Theurer, Staten
F-104D sidestick control system

US Naval Postgraduate School NPS-57LN70071A, 1970, Layton
A simulator evaluation of pilot performance and acceptance of an aircraft rigid cockpit control system

SAE 710388, 1971 Neal
The influence of bobweights and downsprings on flying qualities

- Discusses the possible undesirable side effects.

AFFDL-TR-71-16, 1971, Hall
Design and evaluation of primary hand controllers for fighter aircraft

NASA TN D-7062 Holleman, Powers
Flight investigation of the roll requirements for transport airplanes on the landing approach

- Wheel force was satisfactory at less than 1·6 N/deg for 45° to 60° maximum deflection, for rate of 12 deg/sec and 1 sec. roll mode.

Calspan Report CAL No. AK-5101-F-2, 1972, Eckhart
Investigation of a side-arm controller during in-flight simulation of an unaugmented space shuttle orbiter in the unpowered landing approach

Aircraft Engineering, Vol. 44, Aug. 1972
Variable feel simulation. (High performance jet aircraft variable feel flight control systems for simulation of aerodynamic reaction forces proportional to dynamic pressure)

- Discusses control law variations and duplex feel systems.

NASA TM 72867 Smith
Analysis of a lateral PIO experienced on the first flight of the YF-16 aircraft

- Excessively low lateral stick force was a significant factor

Society of Experimental Test Pilots 1973 Report to the Aerospace Profession, Berven
BD-5 flight test program report

Calspan Report No. AK-5280-F-3, 1974, Hall, Huber, Close
Development of an airplane electrohydraulic variable feel sidestick flight controller

Aircraft Engineering, Vol. 46, May 1974
MRCA systems and related equipment - hydraulic system and flying controls

- Describes Tornado duplex hydro-pneumatic pitch feel system

AFFDL-TR-74-52, 1974, Larson et al
Vol. I Military transport (C-141) fly-by-wire program: Control law development, system design and piloted simulation evaluation.

USAF Test Pilot School Letter Report, March 1975, Farrari et al
BD-5J limited performance and flying qualities evaluation

AFFDL-TR-75-39 Hall, Smith
Flight investigation of fighter side-stick force-deflection characteristics

- Best configuration was a low control force gain with a small amount of stick motion.

NASA TN-D-7884, 1975 Wittler
Apollo experience report - Crew station integration, Vol. III - Spacecraft hand controller development

AFFDL-TR-75-58, Vol. I 1975, Mattes, Asicla
High acceleration cockpit controller locations

AGARD Symposium, Flight Test Techniques, Porz Wahn 1976, Wuennenberg, von Meier
Flight testing and evaluation techniques for the determination of handling qualities

- Describes variable feel force and auto-trim mechanical system.

NASA Advanced Control Technology and its Potential for Future Transport Aircraft Conf., Schenk, McMaster
The F-12 series aircraft approach to design for control system reliability

- Includes description of feel and trim system.

AGARD Flight Simulation/Guidance Systems Simulation, Lipscombe, Lewis
Feel force system with an inertia reduction capability

- Single and twin stick feel force system able to represent high or low inertia.

NASA TN D-8027 Kempel, Dana, Sim
Flight evaluation of the M2-F3 lifting body handling qualities at Mach Nos. from 0·3 to 1·61

- Contains useful comments about the sidestick characteristics.

NASA TN D-8176 Gilbert, Nguyen, Gunst
Simulator study of the effectiveness of an automatic control system designed to improve the high angle of attack characteristics of a fighter airplane

- Rigid sidestick controller in YF-16 was not satisfactory.

AFFDL-TR-77-34, 1977, Cima et al
Limited flight evaluation of sidestick controller force-deflection characteristics on aircraft handling qualities

USAF Test Pilot School Letter Report, 9th Dec. 1977, Saxon et al
Limited flight evaluation of sidestick controller force-deflection characteristics on aircraft handling qualities

RAE TN 78065 Chisman, Port
Some implications on cockpit design of the use of reclined seats in combat aircraft

- Has some comments on centre stick and throttle.

AFFDL-TR-78-171, 1978 Smith, Miller
An evaluation of sidestick force-deflection characteristics on aircraft handling qualities

- Discusses the effects of the stick motion on the satisfactory force-response gradients. Best had light to moderate force gradients with moderate motion.

Air Force Test Pilot School (unpublished AFFTC memo for the record), Duprey
Sidestick controller design criteria

AGARD CP-260, 1978 Mooij, de Boer, van Gool
A simulator investigation of handling quality criteria for CCV transport aircraft

- Gives two-slope pitch and three-slope roll sidestick force gradients.

USAF Test Pilot School Letter Report, 5th June 1979, Cornell et al
Limited flight evaluation of sidestick controller force-deflection characteristics on aircraft handling qualities

Air Force Test Pilot School (unpublished AFFTC letter report), Dec. 1979, Caravello et al
Limited flight evaluation of acceptable sisdestick longitudinal deflection gradients as a function of aircraft longitudinal dynamics

NACA TP-1494, 1979, Anderson
A comparison of the handling qualities of the VAK-191B with the requirements of AGARD Report 577 and MIL-F-83300

- Comments on adverse effects on handling of deficiencies in the mechanical control system qualities

Air Force Test Pilot School (unpublished AFFTC letter report), 1980, Mohr et al
Limited evaluation of the effect of roll mode time constant and asymmetric roll force/response gradients on the handling qualities of the NT-33A sidestick controlled aircraft

NRC Canada Report LR-606, 1981, Sinclair, Morgan
An investigation of multi-axis isometric side-arm controllers in a variable stability helicopter

NASA TM 81972 Kelley, Enevoldson
Limited evaluation of an F-14A airplane utilising an aileron-rudder interconnect in the landing approach

- Without interconnect, sideslip reached 12° for ¾ lateral stick. With the interconnect the handling was very good.

AFAMRL-TR-81-39, 1981, McDaniel
Male and female strength capabilities for operating aircraft controls

Society of Flight Test Engineers, 12th Annual Symposium, 1981, Cord
Sidestick controller design requirements

- Summarises results of series of Air Force Test Pilot School student experiments

NASA CR-165738, 1981, Deam, See, Shane
Research program into nonconventional controllers for general aviation airplanes

AGARD CP-333, 1982 Sinclair
Flight experiments with integrated isometric side-arm

controllers in a variable stability helicopter

- Four-axes rigid controllers were successful, but performance was better with conventional controllers. Addition of limited compliance provided useful feedback.

AGARD CP-333, 1982 Gibson
Piloted handling qualities design criteria for high order flight control design

- Comments on relation between stick feel stiffness and arm jostling in turbulence.

2nd European Annual Conference on Human Decision Making and Manual Control, 1982
Nordström, A mini-sized aircraft manual control

NASA CR-172852, 1983, Landis, Dunford, Aiken, Hilbert
A piloted simulator investigation of side-stick controller/ stability and control augmentation requirements for helicopter visual flight tasks

Rijksluchtvaartdienst, 1983, van Gool, Tigchelaar
Airbus demonstration of side-stick and fly-by-wire control system as proposed for the A-320

AIAA 84-0235-CP, 1984, Aiken, Hilbert, Landis, Glusman
An investigation of side stick controller/stability and control augmentation system requirements for helicopter terrain flight under reduced visibility conditions

Jnl. of Guidance, Control and Dynamics, Vol. 10 No. 6, 1987, Quinn, Cutchins
Limited evaluation of the longitudinal flying qualities of a centerstick aircraft with variations in stick feel parameters

84A19744 NASA Issue 7 Category 3, 1984, Landis, Aiken
An assessment of various side-stick controller/stability and control augmentation systems for night nap-of-earth flight using piloted simulation

Flight Research Laboratory, University of Kansas, 1984, Herrera, Downing, Roskam
Sidestick controllers for general aviation aircraft: a feasibility study

NASA 20th Annuul Conference on Manual Control, Privoznik, Berry, Bartoli
Measurements of pilot time delay as influenced by controller characteristics and vehicles time delays

- Compares Shuttle palm-pivot controller and conventional sticks. Least pilot delay with heavier center stick.

Memorandum M-531, 1985, Clemenkowff (Delft Technical University, The Netherlands)
Ergonomische aspecten bij het ontwerp en installering van een "side stick controller"

- A literature survey and detailed summary of design aspects of sidesticks

NASA CR-3983, 1986, Johnston, McRuer
Investigations of interactions between limb-manipulator dynamics and effective vehicle roll control characteristics

Jnl. of Guidance, Control and Dynamics Vol. 9 No. 5, Oct. 1986 Smith, Sarrafian
Effect of time delay on flying qualities: an update

- Discusses validity of including feel system dynamics in total time delay

Jnl. of Guidance, Control and Dynamics Vol. 10 No. 2, March-April 1987, Johnston, McRuer
Investigation of limb-side stick dynamic interaction with roll control

RAeS International Conference on Helicopter Handling Qualities and Control, London 1988
Morgan.
In-flight research into the use of integrated side-stick controllers in a variable stability helicopter

AIAA 88-4326, 1988, Aponso, Johnston
Effect of manipulator and feel system characteristics on pilot performance in roll tracking

AIAA 88-4327-CP, Baillie, Powers, Shafer
Interaction of feel system and flight control system dynamics on lateral flying qualities

AIAA-88-4609-CP, 1988, Knotts, Bailey
Ground simulator requirements based on in-flight simulation

- Notes the necessity of calibration and documentation of the stick characteristics.

15th European Rotorcraft Forum, Amsterdam Sept. 1989, Baillie, Morgan
An in-flight investigation into the relationships among control sensitivity, control bandwidth and disturbance rejection bandwidth using a variable stability helicopter.

NASA CR-179445, 1990, Bailey, Knotts
Interaction of feel system and flight control system dynamics on lateral flying qualities

AIAA-90-2848-CP, Baillie
Handling qualities research at the Flight Research Laboratory, NAE/NRC, 1980-1990 and beyond

- Comment on rotorcraft four-axes side-arm controllers and improvements with the use of compliance.

47th AHS Annual Forum, Phoenix, 1991, Vol. 2, Parham, Popelka, Miller, Froebel
V-22 pilot-in-the-loop aeroelastic stability analysis

- Models of pilot and control stick feedback used to analyse several pilot-in-the-loop aeroelastic coupling mechanisms.

AGARD CP-508, 1991 Baillie, Kereliuk
An investigation into the use of side-arm control for civil rotorcraft applications

- 4-axes integrated controllers found viable for this application.

AGARD CP-508, 1991 Walchli, Smith
Flying qualities of the X-29 forward swept wing aircraft

- Pitch-roll harmony and control was greatly improved by halving the pitch travel.

AGARD CP-508, 1991 Nicholas, deBoer, van Engelen, Huynh, Shafranek
Handling qualities guidelines for the design of fly-by-wire flight control systems for transport aircraft

- With FCS hold terms, pilots tended to apply sidestick commands in separate axes in a pulse-like manner, with possible unintended cross-coupling.

Proceedings of the 5th IFAC Symposium on Analysis, Design and Evaluation of Man-Machine Systems, The Hague, 1992, van Paassen
Biomechanics in aircraft control

- Examines roll ratchet.

AIAA-92-4172-CP, 1992, Siracuse, Govindaraj
The VISTA/F-16 programmable feel system

AGARD Report 335, PIO Workshop, Turin 1994 Gibson
Looking for the simple PIO model

- Discusses the relationship between stick characteristics and the modelling of pilot stick motions in PIO.

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14. Abstract

Since the earliest days of manned flight, designers have to sought to assist the pilot in the performance of tasks by using stick and feel systems to bring these tasks within the bounds of human physical capabilities. This volume describes stick and feel systems in two parts. Part one describes the technologies which have been developed throughout the history of 20th Century aviation. Part two describes how modern systems dynamics interact with the human pilot. It is hoped that the design lessons and approaches outlined in this volume will contribute to a better understanding and appreciation of the importance of force-feel system design in aircraft/rotorcraft flight control.

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